NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

RAPID ESTIMATION OF BUILDING DAMAGE BY CONVENTIONAL WEAPONS

by

Choon Ming Martin Tan

September 2014

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REPORT DOCUMENTATION PAGE				*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2014		**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE RAPID ESTIMATION OF BUILDING DAMAGE BY CONVENTIONAL WEAPONS				**5. FUNDING NUMBERS**
6. AUTHOR(S) Choon Ming Martin Tan				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000				**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A				**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited				**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

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The objective of this thesis is to develop a code using open-source information and commercially available software to evaluate the degree of damage to a building by conventional weapons. For this thesis, a model in Microsoft Excel will be developed to examine how a warhead will interact with different types of structures. The computational power of MS Excel and Visual Basic will be harnessed to provide the user with a reasonable model of the degree of damage to the building of interest.

This model, named "Building Damage Program," is based upon the theories employed in the Facility and Component Explosive Damage Assessment Program manual, The Architect's Studio Companion: Rules of Thumb for Preliminary Design. and Weaponeering: Conventional Weapon System Effectiveness.

14. SUBJECT TERMS Rapid Estimation, Building Damage, Conventional Weapons			**15. NUMBER OF PAGES** 107
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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RAPID ESTIMATION OF BUILDING DAMAGE BY CONVENTIONAL WEAPONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2014

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LIST OF ACRONYMS AND ABBREVIATIONS

BDP	Building Damage Program
FACEDAP	Facility and Component Explosive Damage Assessment Program
FIST	Fast Integrated Structural Tool
GUI	Graphical User Interface
JMEM	Joint Munitions Effectiveness Manual
JWS	JMEM Weaponeering System
ME	Microsoft Excel
NPS	Naval Postgraduate School
NCEL	Naval Civil Engineering Laboratory
P-I	Pressure-Impulse
SwRI	Southwest Research Institute
TNT	Trinitrotoluene
VB	Visual Basic
K-B	Kingery-Bulmash

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ACKNOWLEDGMENTS

First, I would like to thank Professor Morris Driels for the guidance and patience he provided throughout this period. I am very grateful for the weekly meetings and technical discussions we had in the course of completing this thesis.

Secondly, I would like to thank Professor Christopher Adams for providing his insights and advice to this thesis.

Finally, I would like to express my immense gratitude to my wife, Toh Yi Harn Brenda, for her support, encouragement, and sacrifice during my absence from home. This would not be possible without her taking care of our newborn son, Isaac Tan, 8,500 miles away on the other side of the Pacific Ocean.

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I. INTRODUCTION

A. BACKGROUND

Due to the shifting paradigms of modern-day warfare, new threats are constantly being identified. Military forces in the world are evolving more efficient ways to operate their assets in the most effective and strategic manner. Many times, commanders on the ground require a quick assessment on the potency of a certain munition on specific targets. During such situations, time is not a luxury that can be spared for complex and detailed simulations to be performed.

While there are high-fidelity packages available, such as the JMEM Weaponeering System (JWS) Fast Integrated Structural Tool (FIST) for assessing building damage, this normally requires intensive computational power and time for results to be produced. In addition, the database used is classified and is only available to a limited user base [1]. FIST provides an accurate number representing the degree of damage to a building but leaves it to the user to interpret the possibility of building collapse [1].

The advantage of the program developed in the course of this thesis is that it utilizes open-source information and models to provide an assessment of building damage to the user. Moreover, the time required is extremely short. The user or a commander on the ground, who requires a quick assessment of the degree of damage by deploying a certain type of munition, will be able to make a decision almost instantaneously based on the results of this program.

This program is named "Building Damage Program" (BDP), and is based upon the theories employed in *Weaponeering: Conventional Weapon System Effectiveness* [1] by Morris Driels, the *Facility and Component Explosive Damage Assessment Program (FACEDAP)* manual [2] and *The Architect's Studio Companion: Rules of Thumb for Preliminary Design,* [3] by Edward Ellen and Joseph Iano.

B. OBJECTIVES

The objective of this thesis is to develop a code using open-source information and commercially-available software to evaluate the degree of damage to a building. For this thesis, a model will be developed using Microsoft Excel (ME) to examine how a warhead will interact with different types of structures. The computational power of ME and Visual Basic (VB) will be harnessed to provide the user with a reasonable model of the degree of damage to the building of interest.

The program will gather input from the user such as weapon, building size, and the method of construction. With this information, BDP will predict the number of columns that will fail and similar to FIST, it provides results to the user for interpretation on whether the building will collapse. This program will have a limited selection of building structure types but can be extended to include more options in the future, as needed.

Several benefits will be brought about by this program. First, it uses open-source information. Secondly, it is fast and does not require a long simulation time. Thirdly, users will not require special training, as the BDP runs on commonly used that is widely available.

C. BUILDING DAMAGE PROGRAM OVERVIEW

Figure 1 illustrates the floor plan of a building divided into cells of dimensions one-foot by one-foot, making up the footprint of the building. Columns that support the building are denoted by blue squares. BDP works by having the warhead detonating at the first cell and calculates how many columns are destroyed. This is repeated for every cell. At the end of the simulation, every cell will contain a number that corresponds to the number of columns destroyed if the warhead detonates in that cell.

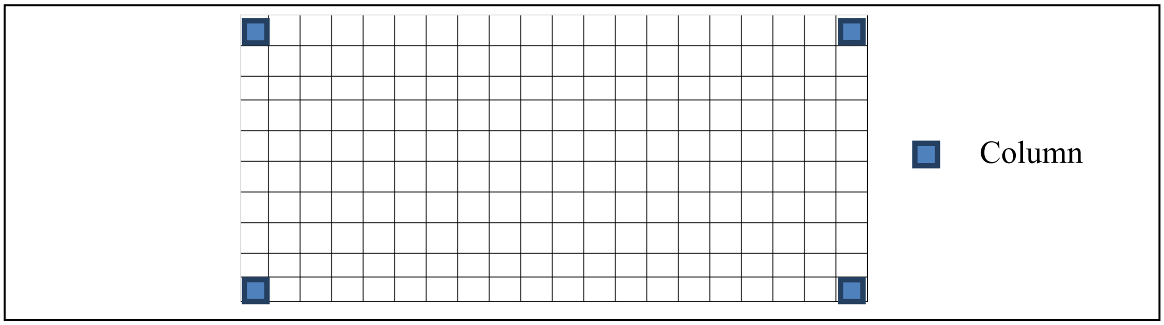
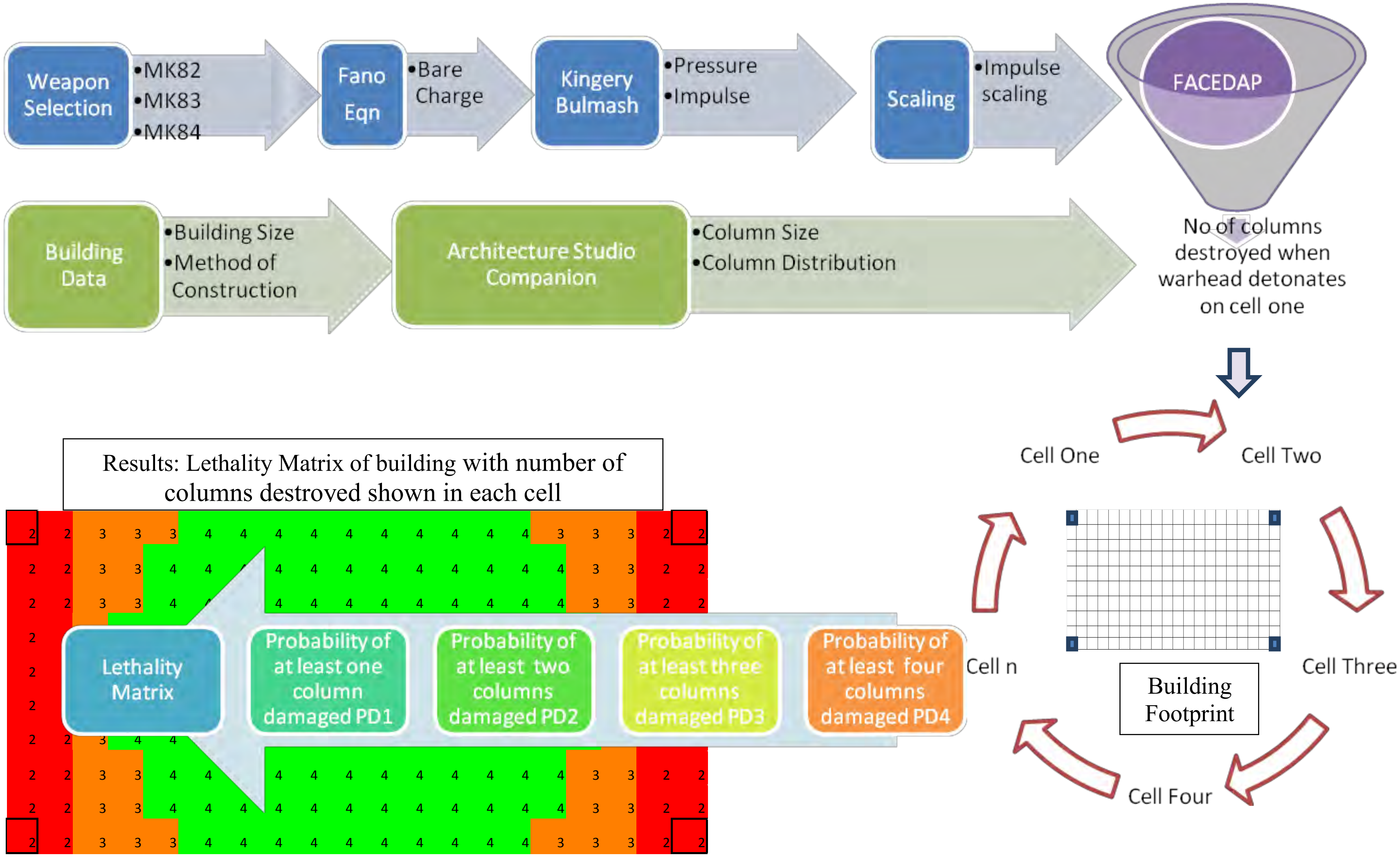


Figure 1. Building footprint.

The flowchart shown in Figure 2 illustrates how information is passed from one module to another within the BDP during the simulation.

Figure 2. Flowchart of building damage program.



1. After the user has selected the type of weapon, the explosive yield that is produced by the warhead will be calculated using the Fano equation. It is assumed that the detonation of the warhead produces a blast wave that is analogous to a spherical charge of TNT exploding in free space. Therefore, the Fano equation serves as a useful tool in relating the weight of explosive that is enclosed in the warhead to an equivalent uncased weight of TNT by taking into account the metal casing that is used to enclose the warhead.

2. The equivalent explosive yield obtained from the Fano equation is then passed into the Kingery-Bulmash (K-B) equations for further calculations. The K-B method computes the impulse and pressure based on the explosive weight and distance from detonation. The impulse obtained is then scaled as shown by equation 1.1 before input into FACEDAP for further analysis.

3. The impulse obtained from the K-B method, $I_{K\text{-}B,}$ needs to be rescaled for usage in FACEDAP. This is performed by Equation (1.1) where W_T is the equivalent uncased charge weight in TNT.

$$I_{FACEDAP} = I_{K-B} \frac{W_T^{1/3}}{1000} \tag{1.1}$$

4. Before FACEDAP is able to process further, it will require information regarding the target building. This data is provided by the literature, *The Architect's Studio Companion: Rules of Thumb for Preliminary Design* [3]. This text provides data on the column size and column distribution based on the method of construction selected by the user.

5. Within FACEDAP, there are 24 different structural elements available. However, this thesis uses only data on interior concrete column. With all the above in place, FACEDAP determines if the column will fail based on a selected warhead detonating at a certain distance away.

6. The floor plan of a building is divided into cells of dimensions one foot by one foot, making up the footprint of the building. A warhead is simulated to detonate on the first cell of the footprint as shown in Figure 3. FACEDAP determines if the column nearest to cell one will be destroyed. This is performed for all the columns supporting the building while repeating the warhead detonation on the first cell. The total number of columns that is destroyed is then summed up.

7. BDP then moves on to the second cell and determine how many columns will be destroyed if the warhead detonates on the second cell. This process

is repeated for all the cells up till the nth cell in the building footprint as shown in Figure 3.

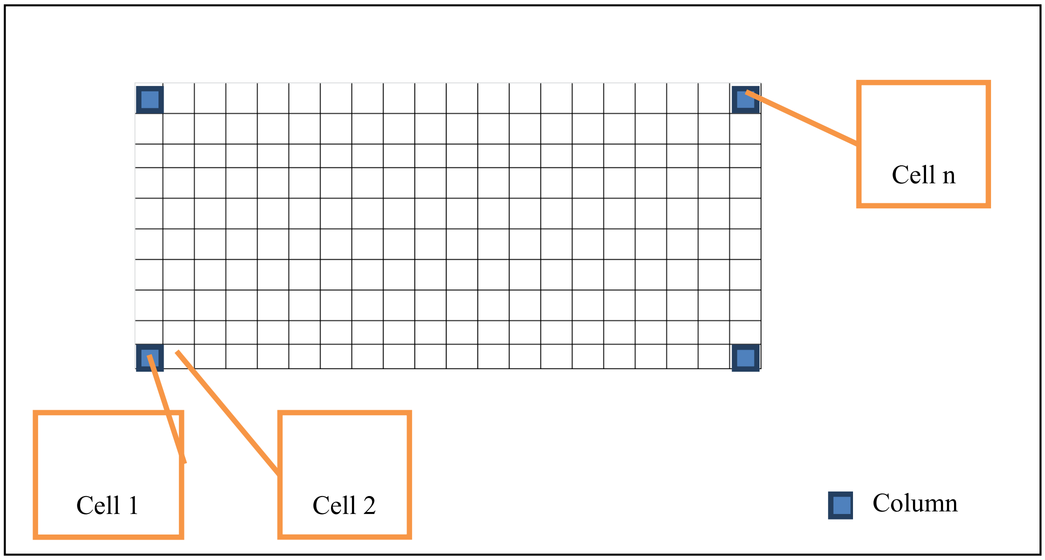


Figure 3. Building footprint with n cells.

8. The end result will be a lethality matrix showing the number of columns that will be destroyed if the warhead lands on a particular cell. In addition, the probability of having 1, 2, 3 and 4 columns destroyed will be generated. With this information, the user will decide if the building will collapse.

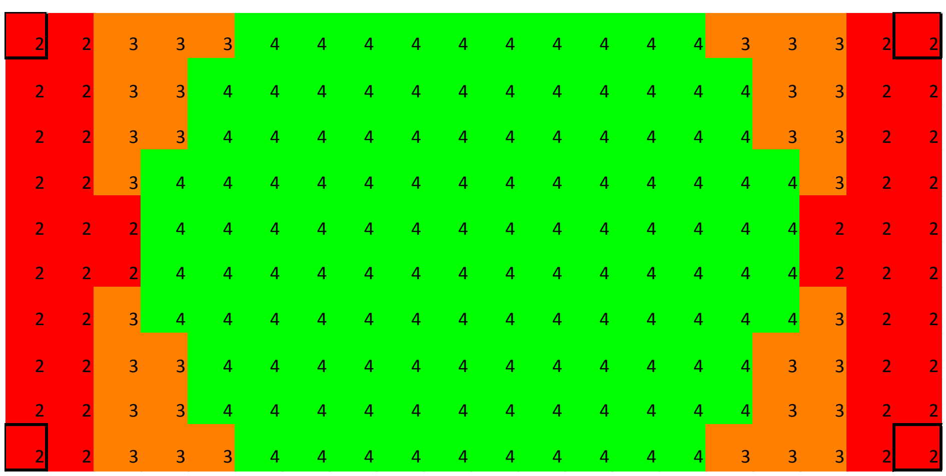


Figure 4. Lethality matrix with number of columns destroyed shown in each cell.

This idea of probability of columns failure is very similar to FIST where a number is provided to the user for interpretation on the degree of damage to the building. In order to use FIST, a model of the target building will need to be generated and imported into the program [1]. Also, details such as impact conditions, structures in the line of weapon penetration, material of the structure and location of the weapon will need to be furnished [1]. With all the above information, FIST simulates the penetration process, mimics the blast effects and determines the degree of damage to the structures of the building [1]. FIST requires as much information about the building as possible to provide an accurate result [1]. For example, number of floors, age of the building, number of windows and dimensions etc. [1]. While it is advantageous to have a high fidelity program producing accurate results, a lot of effort will be required to gather the information for input. Also, with more details that are entered into the simulation, the longer it takes to generate results. In many instances, time may not be a luxury commodity that is available during a conflict. A quick assessment delivered in a timely manner based on preliminary intelligence may be more useful than a more accurate result furnished much later.

With this primary motivation in mind, the BDP is developed to bridge this gap. To enhance the usability of the program, it will be developed on a platform that is available to many. This is why Microsoft Excel is selected for this endeavor. It is hoped that future commanders and combatants in the midst of the conflict will benefit from using this tool.

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II. FANO EQUATION AND THE METHOD OF KINGERY-BULMASH

A. BACKGROUND

Detonation from a warhead produces a blast wave that propagates from the center of the explosion outward in a spherical manner. This blast wave will weaken over the distance, because the energy is lost as the wave travels. A point nearer to the explosion will experience a larger pressure and impulse compared to a point that is further away. However, this decrease in pressure and impulse over distance does not follow a simple linear decrease.

To determine the effective explosive yield contained in a warhead, the Fano equation is used to take into account that the charge is encased in a metal container. The energy that goes into propelling the metal case fragments need to be accounted for. After the equivalent explosive yield is determined, the Kingery-Bulmash (K-B) method is used to calculate the pressure and impulse at a distance away. This will be the distance between the point of detonation and the column.

This chapter discusses the Fano equation and the K-B method with information referenced from [1] and [4]. The modified Fano equation will be presented and explained to illustrate how an encased warhead can be reduced to an equivalent uncased explosive charge of TNT. The K-B method will also be described and shown how it can be adapted for use with FACEDAP.

B. FANO EQUATION

Equation (2.1) shows the original form of the Fano equation referenced from [4],

$$W_u = W\left[0.2 + \frac{0.8}{1 + \frac{2M}{c}}\right] \tag{2.1}$$

where,

W_u = uncased charge weight in units of (lb)

W = weight of explosive contained in the warhead (lb)

c = charge weight per unit length (lb/in)

M = metal weight per unit length (lb/in)

"Over the years, the Fano equation has been altered and the following is the modified Fano equation that is commonly used to calculate the proportion of energy that generates the blast" [4],

$$W_u = W\left[0.6 + \frac{0.4}{1 + \frac{2M}{c}}\right] \tag{2.2}$$

where,

W_u = uncased charge weight (lb)

W = weight of explosive contained in the warhead (lb)

c = charge weight per unit length (lb/in)

M = metal weight per unit length (lb/in)

As illustrated in Equation (2.2), the uncased charge weight is represented by W_u. This is the resulting explosive yield that is delivered by the warhead, and represents the source of energy that goes into producing the blast wave [4]. Example 2.1 illustrates how the Fano equation can be used to calculate the uncased charge weight for a Mark 84 warhead.

Example 2.1

Given the following parameters of a Mark 84 warhead, estimate the uncased explosive weight W_u.

W = 945 lb, Metal Weight = 1055 lb, Length = 129 in

Solution:

Therefore,

$$c = \frac{945}{129} = 7.325$$

$$M = \frac{1055}{129} = 8.178$$

Applying the modified Fano equation,

$$W_u = W \left[0.6 + \frac{0.4}{1 + \frac{2M}{c}} \right]$$

$$W_u = 945 \left[0.6 + \frac{0.4}{1 + \frac{2(8.178)}{7.325}} \right]$$

$$W_u = 683.9 \ lb$$

the uncased explosive weight of Mark 84 is 683.9 lb.

Figure 5 illustrates the amount of charge weight available for air blast after taking into account the case to charge mass ratio by using the modified Fano equation [4]. As the case becomes heavier, less energy is left to generate the blast [4]. The modified Fano equation is still an estimate and may not be accurate under all circumstances [4].

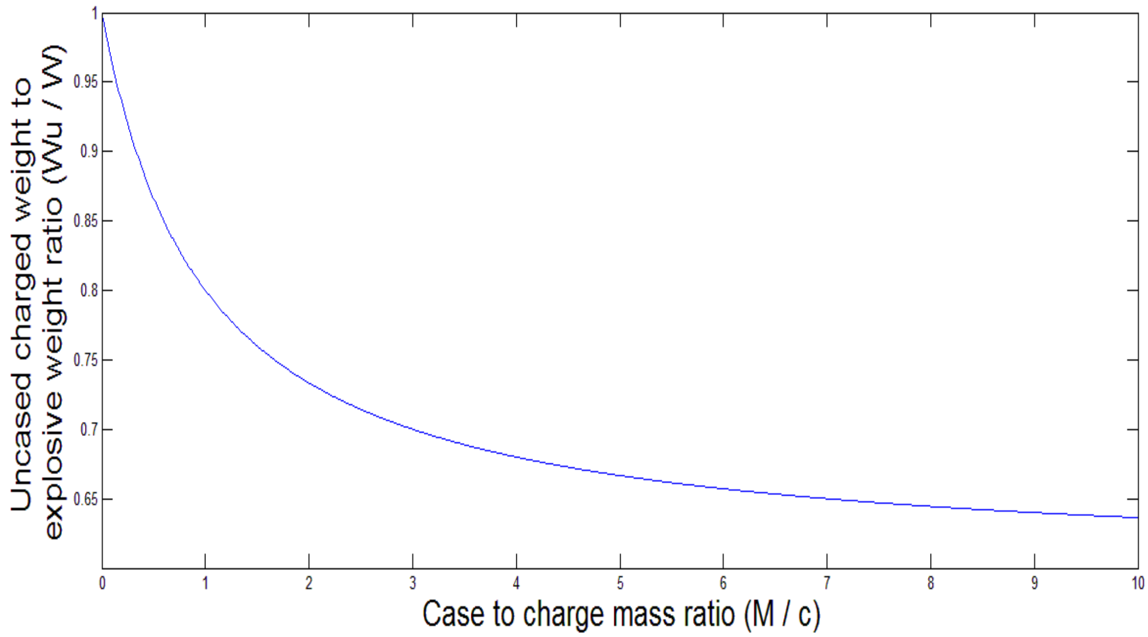

Figure 5. Fano equation in graphical form (After [4]).

Figure 6 is “generated by Dr. Jane Dewey back in the 1960s where she conducted experiments at the Army Ballistic Research Laboratory in Aberdeen” [4]. The Fano equation appears to be more representative of the steel case data compared to other materials [4]. In the steel case example, “there is a still a larger scatter for ratios between 0.2 and 0.06” [4]. However, the Fano equation is still widely used as a good estimate for explosive yield estimation and accounting for the energy that is converted to kinetic energy to propel the warhead fragments [4].

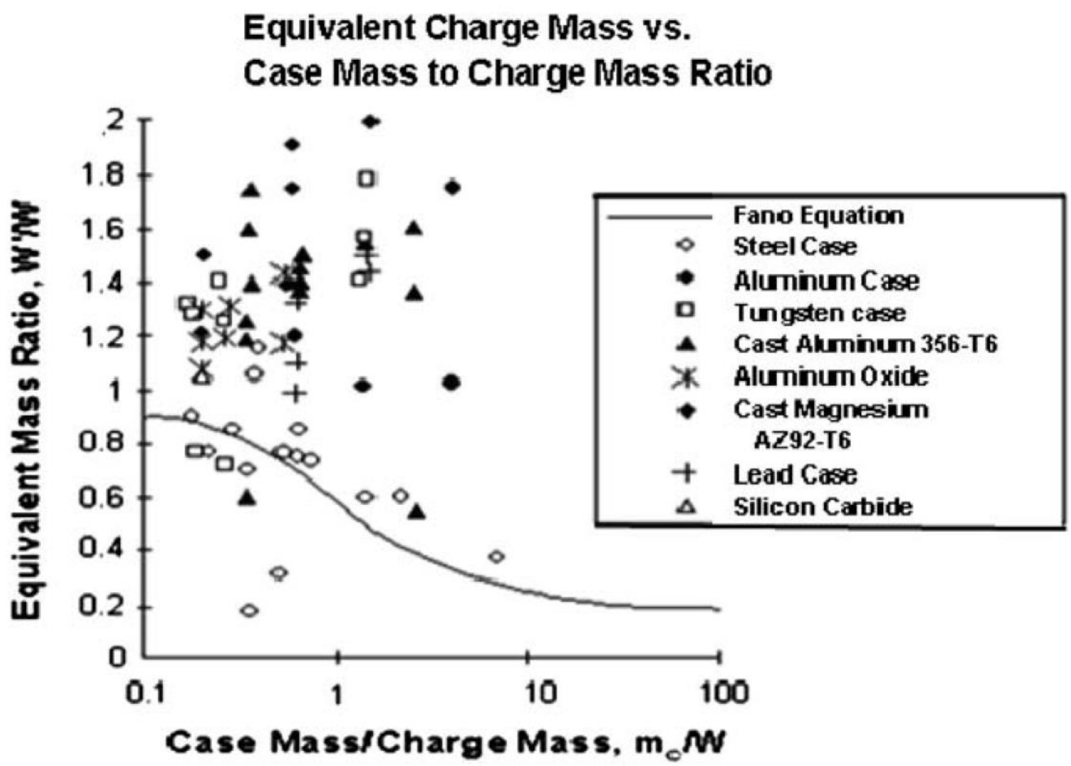

Figure 6. Fano equation vs. live detonation experiments (from [4]).

Other than accounting for the casing in a warhead, the type of charge that goes into the warhead has an effect on the blast wave produced. In order to compare between warheads, different types of explosives used have to be normalized to an equivalent explosive weight of Trinitrotoluene (TNT) [1]. Table 1 shows the multiplier factor that can be used to scale the different types of explosives to an equivalent weight of TNT.

Table 1. Factors for different types of explosives (After [1]).

Type of Explosive	Multiplier Factor M
TNT	1.0
H-6	1.35
Tritonol	1.07
Comp B	1.11

Comp A3	1.07
Comp C4	1.30
Explosive D	0.92
HBX-1	1.17
HBX-3	1.14
Minol II	1.20

The equivalent explosive yield, $W_{T,}$ is given by Equation (2.3) referenced from [1].

$$W_T = MW_U \tag{2.3}$$

Example 2.2

Calculate the equivalent charge weight in TNT of the Mark 84, given that the explosive filling used is Tritonol.

Solution:

$$W_T = MW_U$$

$$W_T = 1.07(683.9lb)$$

$$W_T = 731.7\ lb$$

The equivalent charge weight in TNT of the Mark 84 is 731.7 lb.

The above methods provide simplified approaches to improve the accuracy of blast calculations.

In summary, this section covered two technical aspects of reducing different warheads to the same baseline for a fair comparison. The first is by using the Fano equation to convert a cased warhead to an uncased explosive situation. Secondly, different types of explosive fills can be normalized to an equivalent TNT fill.

C. THE METHOD OF KINGERY-BULMASH (K-B)

The previous section details how an equivalent explosive yield from different warheads can be normalized to the same baseline for calculation. After this information is computed, the next step will be to determine the characteristics of the blast wave. One popular technique is the K-B method. The K-B curves were created by Charles Kingery and Gerald Bulmash using a combination of experimental measurements and other references available to them [4]. According to their method of creating curves, “the curves may be fitted to a polynomial of the 11th order” [4].

With the K-B curves, several blast parameters can be obtained based on the distance from the point of detonation. For example, parameters such as incident impulse, incident pressure, time of arrival, and positive phase duration can be calculated based on distances by using a simple expression [1]. Essentially, the K-B method seeks to describe the blast wave with critical parameters by taking into account attenuation of the blast energy over a distance. It is noted at this juncture that the distance from the point of detonation has to be scaled with the explosive weight before the K-B method can be used.

The first step is to determine the scaled range using Equation (2.4) referenced from [1].

$$Z = \frac{X}{W^{1/3}} \tag{2.4}$$

where,

Z = scaled distance (ft/lb$^{1/3}$)

W = explosive weight (lb)

X = distance from detonation (ft)

Using the Kingery-Bulmash curves shown in Figure 7, parameters such as pressure and impulse can be obtained.

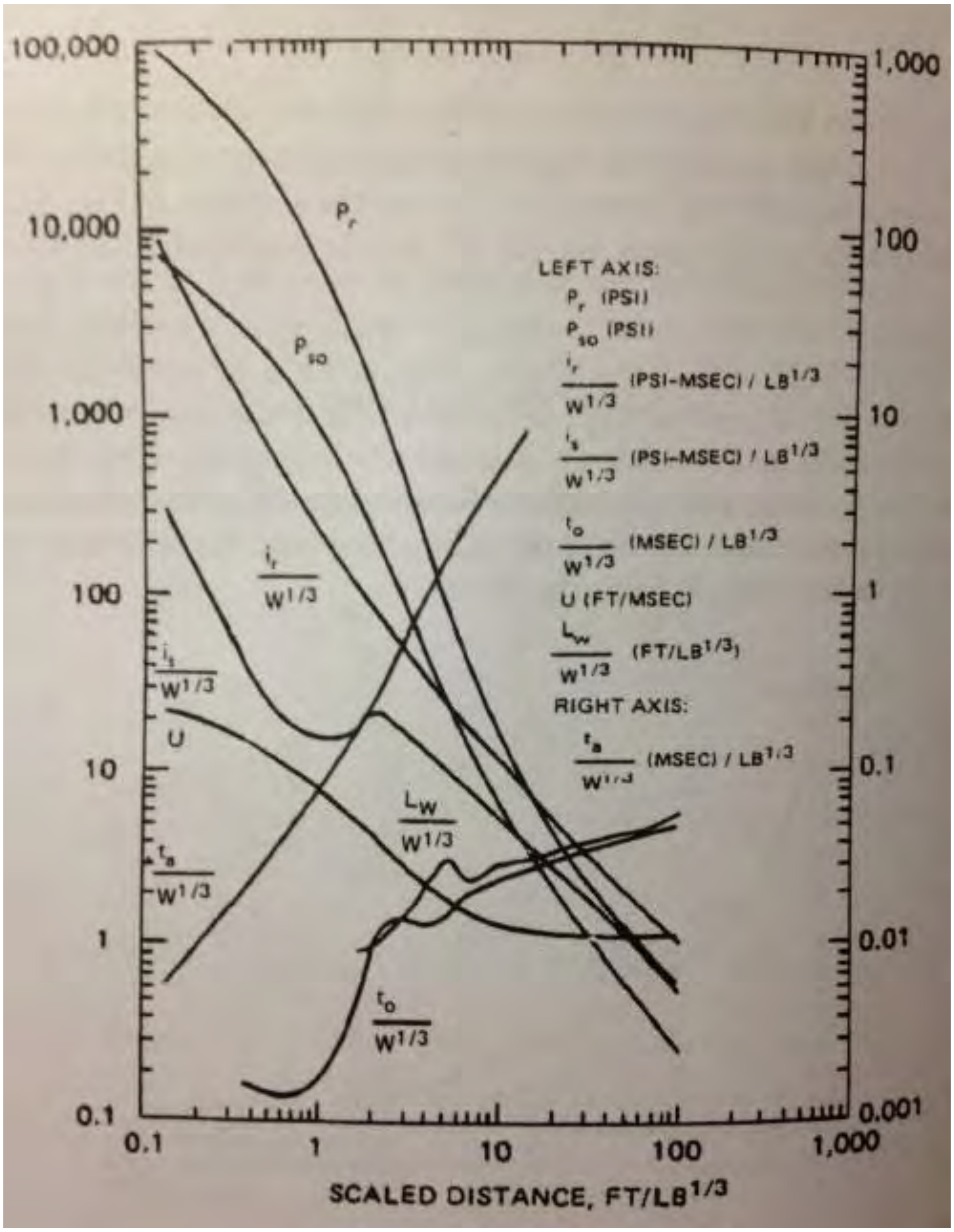

Figure 7. Kingery-Bulmash curves (After [1]).

The parameters listed in Figure 7 are defined as in the following [1].

P_r = peak pressure at reflected surface

P_{so} = peak pressure in incident wave

i_r = impulse applied to reflect surface

i_{so} = impulse of incident wave

t_0 = wave duration

L_w = wavelength of incident wave

t_a = arrival time

Example 2.3

Using the Kingery-Bulmash curves shown in Figure 7, we will estimate the incident pressure P_{so} and incident impulse i_s 25 ft away from the detonation of a Mark 84.

Solution:

Using Equation (2.4), we calculate the scaled range Z,

$$Z = \frac{X}{W^{1/3}}$$

$$Z = \frac{25}{731.7^{1/3}}$$

$$Z = 2.7743 \frac{ft}{lb^{1/3}}$$

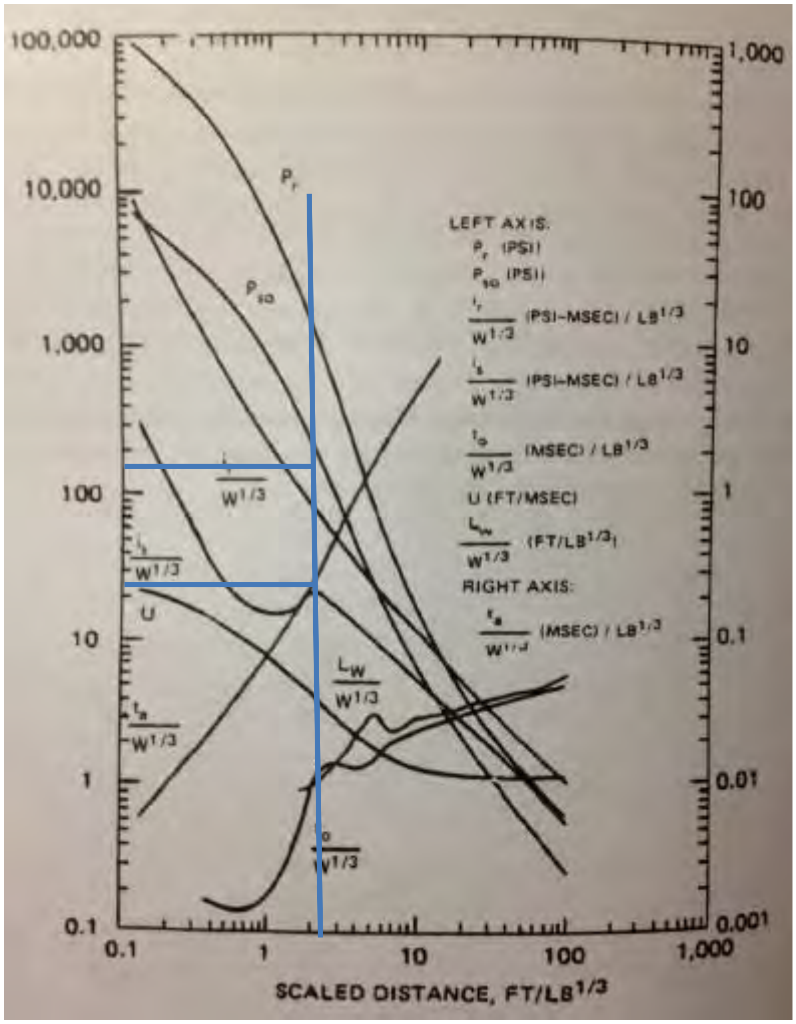

Figure 8. Kingery-Bulmash curves (After [1]).

From the graph in Figure 8 at $Z = 2.7743 \dfrac{ft}{lb^{1/3}}$,

P_{so} = 160 psi and $\dfrac{i_s}{W^{1/3}} = 25$ psi-ms/lb$^{1/3}$

To obtain i_s in psi-s, the following step is performed,

$$i_s = \frac{25(W^{1/3})}{1000} = \frac{25(731.7^{1/3})}{1000}$$
$$= 0.2252 \;\; psi - s$$

The incident pressure is 160 psi and the incident impulse is 0.2252 psi-s at 50 ft from the detonation of a Mark 84.

Instead of reading data from the K-B curves shown in Figure 8, polynomials have been fitted for convenience purposes. Using the polynomial equation, blast parameters such as pressure and impulse can be calculated [1].

After obtaining the scaled distance, Z, Equation (2.5) is used to find parameter T, referenced from [1].

$$T = \log_n(\mathrm{Z}) \tag{2.5}$$

With T, parameter F_p can be obtained by using Equation (2.6), referenced from [1].

$$F_p = \exp\left[A + BT + CT^2 + DT^3 + ET^4 + FT^5 + GT^6\right] \tag{2.6}$$

where,

F_p = General parameter (pressure, impulse, time etc)

A, B, C, D, E, F, G = coefficients shown in Tables 2 and 3.

Example 2.4

Use Equations (2.5) and (2.6) to verify the results obtained in example 2.3.

Solution:

$$\begin{aligned} T &= \log_n(\mathrm{Z}) \\ &= \log(2.7743) \\ &= 1.02037 \end{aligned}$$

Using Equation (2.6) with values of A, B, C, D, E, F and G obtained from Table 2,

$$\begin{aligned} P_{so} &= \exp[6.9137(-1.4398)(1.02037) + (-0.2815)(1.02037)^2 \\ &+(-0.1416)(1.02037)^3 + (0.0685)(1.02037)^4 + 0 + 0] \\ &= 160.02 \ \ psi \end{aligned}$$

$$\frac{i_s}{W^{1/3}} = \exp[0.911 + (7.26)(1.02037) + (-7.459)(1.02037)^2$$
$$+(2.96)(1.02037)^3 + (-0.432)(1.02037)^4 + 0 + 0]$$
$$= 25.25 \;\; \frac{psi - ms}{lb^{1/3}}$$

$$i_s = \frac{25.25(W^{1/3})}{1000} = \frac{25.25(731.7^{1/3})}{1000}$$
$$= 0.2275 \;\; psi - s$$

The results obtained are very close to the numbers shown in example 2.3

Table 2. Simplified Kingery airblast coefficients (After [1]).

POSITIVE PHASE DURATION, T (ms/kg^1/3)							
RANGE, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.2-1.02	0.5426	3.2299	-1.5931	-5.9667	-4.0815	-0.9149	0
1.02-2.80	0.5440	2.7082	-9.7354	14.3425	-9.7791	2.8535	0
2.80-40	-2.4608	7.1639	-5.6215	2.2711	-0.44994	0.03486	0
POSITIVE PHASE DURATION, T (ms/lb^1/3)							
RANGE, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.5-2.5	-1.7221	0.45	1.3552	1.1249	-0.05773	-0.608	0
2.5-7	-18.7701	55.0513	-60.4348	32.0236	-8.3256	0.8817	0
7-100	-13.0597	19.7805	-11.2975	3.2552	-0.4647	0.02624	0
INCIDENT IMPULSE, II (kPa-ms/kg^1/3)							
RANGE, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.2-0.96	5.522	1.117	0.6	-0.292	-0.087	0	0
0.96-2.38	5.465	-0.308	-1.464	1.362	-0.432	0	0
2.38-33.7	5.2749	-0.4677	-0.2499	0.0588	-0.00554	0	0
33.7-158.7	5.9825	-1.062	0	0	0	0	0
INCIDENT IMPULSE, I I (psi-ms/lb^1/3)							
RANGE, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.5-2.41	2.975	-0.466	0.963	0.03	-0.087	0	0
2.41-6.0	0.911	7.26	-7.459	2.960	-0.432	0	0
6.0-85	3.2484	0.1633	-0.4416	0.0793	-0.00554	0	0
85-400	4.7702	-1.062	0	0	0	0	0

Table 3. Simplified Kingery airblast coefficients (After [1]).

TIME OF ARRIVAL, TOA (ms/kg^1/3)							
RANGE, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.06-1.50	-0.7604	1.8058	0.1257	-0.0437	-0.0310	-0.00669	0
1.50-40	-0.7137	1.5732	0.5561	-0.4213	0.1054	-0.00929	0
TIME OF ARRIVAL, TOA (ms/lb^1/3)							
RANGE, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.2-4.5	-2.5671	1.5348	0.1313	0.01825	0.003656	-0.008615	0
4.5-100	-1.79097	-0.44021	2.01409	-0.78101	0.13045	-0.0081529	0
INCIDENT PRESSURE, PI (kPa)							
RANGE, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.2-2.9	7.2106	-2.1069	-0.3229	0.1117	0.0685	0	0
2.9-23.8	7.5938	-3.0523	0.40977	0.0261	-0.01267	0	0
23.8-198.5	6.0536	-1.4066	0	0	0	0	0
INCIDENT PRESSURE, PI (psi)							
RANGE, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.5-7.25	6.9137	-1.4398	-0.2815	-0.1416	0.0685	0	0
7.25-60	8.8035	-3.7001	0.2709	0.0733	-0.0127	0	0
60-500	5.4233	-1.4066	0	0	0	0	0
REFLECTED PRESSURE, PR (kPa)							
RANGE, Z (m/kg^1/3)	A	B	C	D	E	F	G
0.06-2.00	9.006	-2.6893	-0.6295	0.1011	0.29255	0.13505	0.019736
2.00-40	8.8396	-1.733	-2.64	2.293	-0.8232	0.14247	-0.0099
REFLECTED PRESSURE, PR (psi)							
RANGE, Z (ft/lb^1/3)	A	B	C	D	E	F	G
0.3-4.0	9.0795	-1.7511	-0.2877	-0.2199	-0.0128	0.0696	-0.0118
4-100	5.1515	9.15826	-11.85735	5.56754	-1.33455	0.16333	-0.008181

Using the Equations (2.4), (2.5) and (2.6), various parameters of the blast waves can be computed at any desired distance away from the point of detonation. For the purpose of this thesis, two critical blast parameters are desired. The two parameters are scaled pressure and impulse. The impulse obtained from the K-B method needs to be rescaled for usage in FACEDAP.

In summary, this chapter provided a quick overview of the Fano equation used to convert explosive yield from different warheads to a common baseline for calculations, and the theory used to describe and calculate various parameters of a blast wave and how they vary with distance from the detonation point.

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III. METHODS OF BUILDING CONSTRUCTION

A. BACKGROUND

So far, this thesis has covered theories used to describe a blast wave, which is insufficient to determine whether a structure will collapse. In addition to determining the pressure and impulse produced by a detonation, the strength, size, and location of the structure will need to be known. It is not easy to get specific answers to the above parameters, because there are many different types of buildings. Buildings range from lightly constructed residential apartments to heavy industry factories that are strongly reinforced. This chapter discusses the construction methods with information referenced from [3].

The first type of buildings addressed in the BDP is the slab and column construction [3]. Columns form the main supporting structures and take the load of the building as shown in Figure 9.

Figure 9. Slab and column construction.

The second type of building addressed in the BDP is the waffle slab and column construction as shown in Figure 10. This form of construction is more robust than the slab and column method and allows the columns to be spaced farther apart [3].

Figure 10. Waffle slab and column construction.

Faced with various building types and methods of construction, it is by no means an easy task to standardize different types of buildings into a common baseline for analysis. What is required is a method to quickly estimate the size of the main supporting columns and their column distribution within the building based on the construction method used by the builders and designers. One option will be to turn to building codes that provides broad overarching guidelines to architects and civil engineers. However, such codes vary by country, and are not detailed enough to provide the data required.

To obtain the structural information required, this thesis uses information from *The Architect's Studio Companion: Rules of Thumb for Preliminary Design* [3].

B. STRUCTURAL SYSTEM SIZING

This section of the literature provides the necessary information for input into FACEDAP. From information gathered from this section, the size of the column and distribution of the columns within the building can be determined. This knowledge is important to further analyze whether the building will collapse.

There are altogether five main categories of structures, including Wood, Masonry, Steel, Site-cast concrete, and Pre-cast concrete [3]. For this thesis, we concentrate on Site-cast concrete structures.

1. Concrete Structural System

Concrete is the most widely-used material in contemporary construction. This material is strong and may be formed into various shapes and sizes [3]. Used together with steel rebar, it can handle both compressive and tensile loads. For concrete structural systems, they can be categorized into site-cast or pre-cast structures [3]. Site-cast structures come with the challenge of being more expensive and containing quality control issues such as dimensional accuracy and surface finish [3]. Pre-cast structures do not face these issues and allow faster construction. Pre-cast structures do have limitations such as transportation and handling restrictions [3].

Similar to the different types of structural systems that have been discussed previously, concrete structures are available in a myriad of varieties such as columns, wall panels, beams, girders, slabs, joists, and waffle slabs [3]. The fundamental support structure that bolsters a building is the column.

Figure 11 shows a graph on sizing site-cast concrete columns using tributary area. Both light-residential constructions and heavy-industry buildings can use this graph as a guide on sizing up the concrete columns required [3].

As the columns are uniformly distributed across the building footprint, the tributary area supported by a column can be estimated by the dividing the area of the footprint by the number of columns [3]. The tributary area can be viewed as the region that exerts a constant pressure of load onto the supporting structure [3]. In this case, the supporting structure is the column.

Example 3.1

Estimate the tributary area supported by a column within Watkins Hall, home of the Department of Mechanical and Aerospace Engineering at the Naval Postgraduate School (NPS), with a footprint of 100 ft. by 90 ft. Assume the 30 columns that support the building are uniformly distributed and there are three levels altogether.

Solution:

Total floor area = 3 x 100 x 90 = 27000 ft^2

Tributary area support per column = 27000/30 = 900 ft^2

Therefore, the tributary area supported by a column is 900 ft^2.

Referring to Figure 11, the size of the column can be selected depending on the activities that take place in the building. For normal loads, values from the top of the solid area are used [3]. For industrial loads that are more substantial, values from the underside of the solid area are used [3].

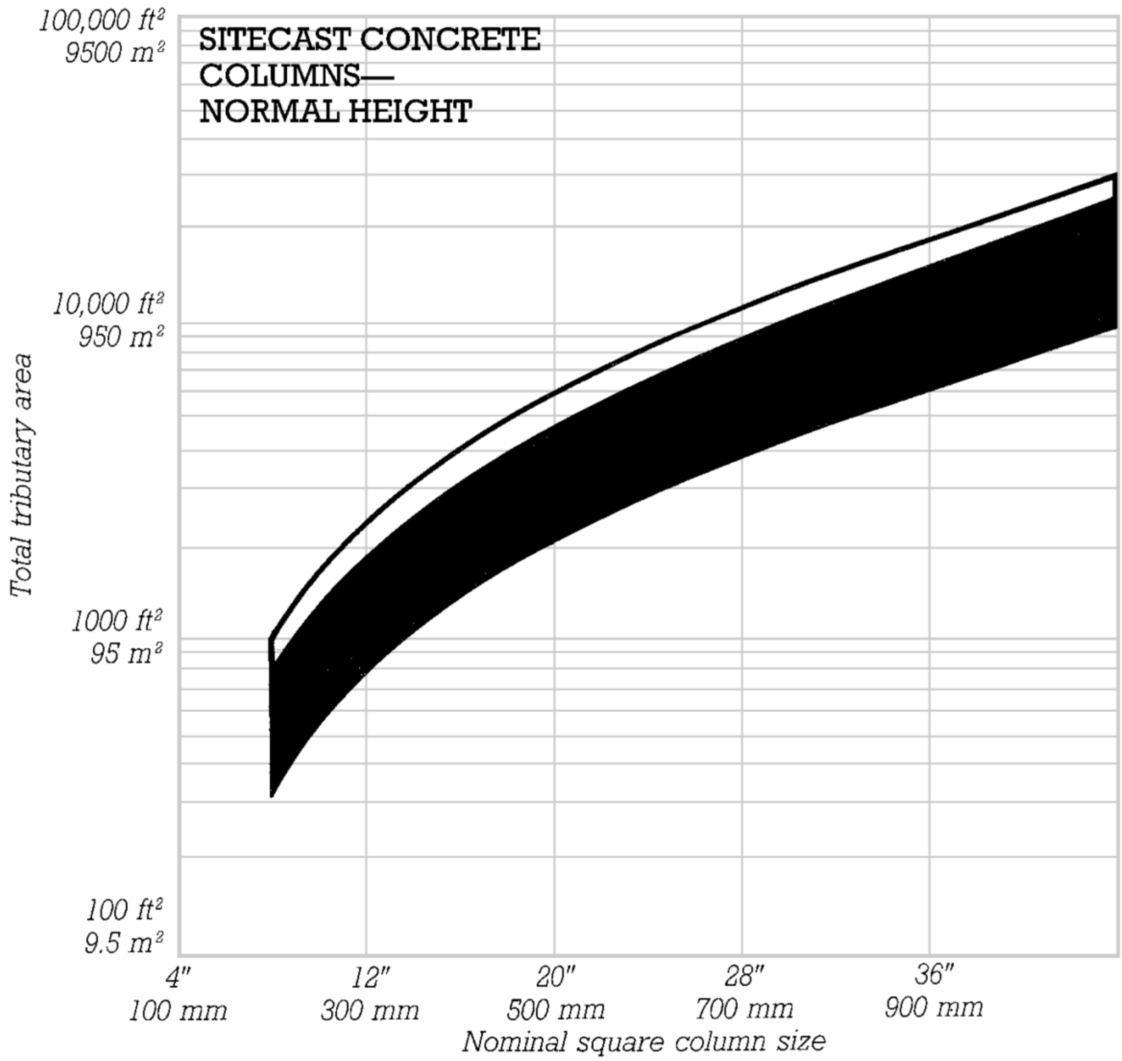

Figure 11. Site-cast concrete column size vs. tributary area (After [3]).

Example 3.2

From example 3.1, it has been calculated that the tributary area supported by column is 900 ft^2. We will estimate the size of a column supporting Watkins Hall assuming it has a one-way slab and column construction. It is an office building; however, one floor houses heavy equipment.

Solution:

Reading from Figure 12, with a tributary area of 900 ft^2, the column size for Watkins Hall is estimated to be about 14 in.

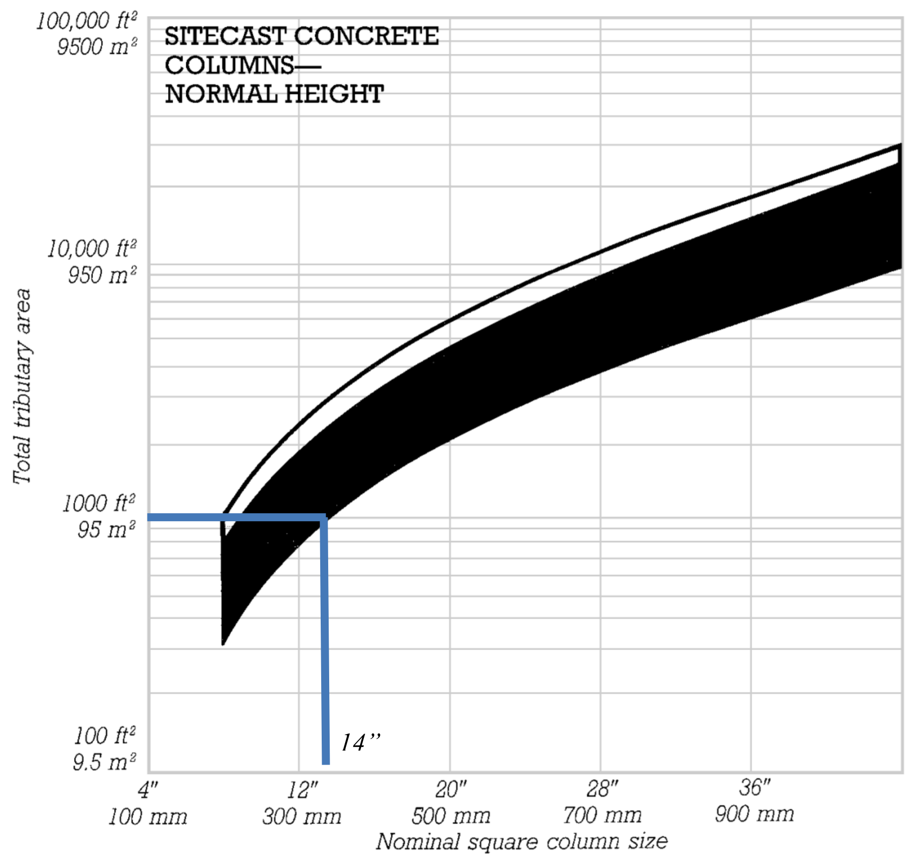

Figure 12. Site-cast concrete column size vs. tributary area (After [3]).

For economical column designs, size of columns should not vary much throughout the building [3]. They should be maintained the same as much as possible [3]. Most buildings follow this rule of design. It is under very rare circumstances that this rule is ignored.

Column distribution in a building should be uniform [3]. This reduces the effort required for the designer in calculating loads distribution and increases the stability of the building. This is to ensure efficient load transfer from the top level all the way down to the ground level [3].

Concrete columns can be combined with various construction components in a building. To be more accurate in determining the column size, it is more important to know how the column is being used. For example, it can be utilized to support a one-way solid slab or a two-way flat plate.

According to the *Structural design guide to the ACI building code* [5], a one-way slab type of construction is defined as "a flexural member with depth small relative to other dimensions, supporting loads applied normal to and directly over its surface, spanning in one direction between parallel supports and reinforced for flexure in that direction only" [5]. On the other hand, "a two-way slab type of construction has both dimensions of length and width relatively the same; and is reinforced so that it will resist flexure in both the directions of the length and width" [5]. With this understanding, the two-way slab construction is expected to be stronger and allows the column to be spaced further apart.

It is important to note that one-way slab construction does not mean that the slab will have beams running in one direction only [3]. It can have beams supporting the loads in one direction and girders running perpendicular to the beams as well [3]. Likewise, two-way slab method of construction does not mandate that it must be reinforced by beams in both directions [3]. One unique example will be the site-cast two way flat plate that does not utilize any beams at all [3]. The relative dimensions of the length and width of the slab are important in determining if it is a one-way or two-way type of construction [3].

At this point, it is important to differentiate between a slab and a plate. The two-way flat plate construction is identified by its absence of column caps or drop panels at the intersection of the column slab interface [3]. When the term two-way flat slab is used, it is understood that such strengthening features have been incorporated into the structure [3].

The following four methods of construction are addressed in the BDP and are the most commonly used in building construction. They are listed in ascending order of strength [3].

1. Site-cast concrete one-way slab
2. Site-cast concrete two-way plate
3. Site-cast concrete two-way slab with beams
4. Site-cast concrete waffle slab

2. Site-cast Concrete One-way Slab

This is the most affordable method of construction and is very much recommended for light loads bearing buildings such as residential homes [3]. Examples of this method of construction are illustrated in Figures 13, 14 and 15. For a one-way slab, the length is normally much longer than the width [3].

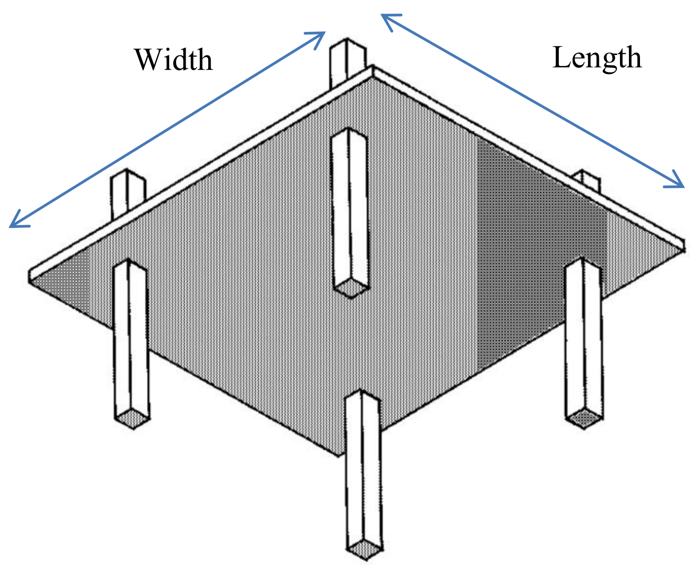

Figure 13. One-way solid slab (After [3]).

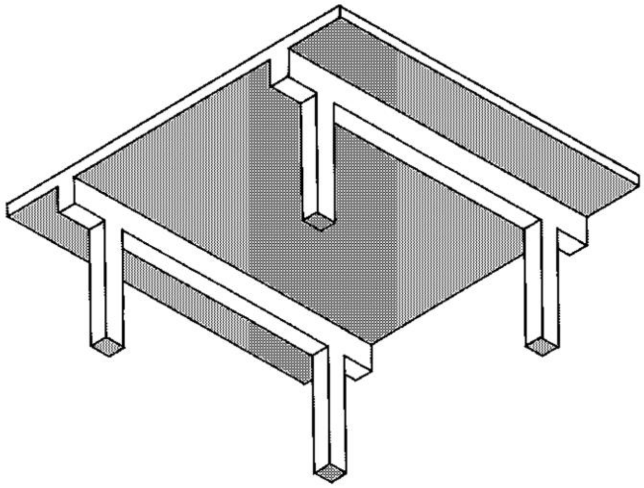

Figure 14. One-way solid slab with beams (After [3]).

Figure 15. One-way solid slab.

3. Site-cast Concrete Two-way Flat Plate

This method of construction is more expensive but stronger than the One-Way Slab methods [3]. Note that the word "plate" is used instead of "slab," as there are no strengthening structures such as column caps and drop panel between the column and the concrete plate [3]. Figure 16 shows an example of this method of construction. As a rule of thumb, for the two-way plate method of construction, the ratio of length to width is normally taken to be less than two [3].

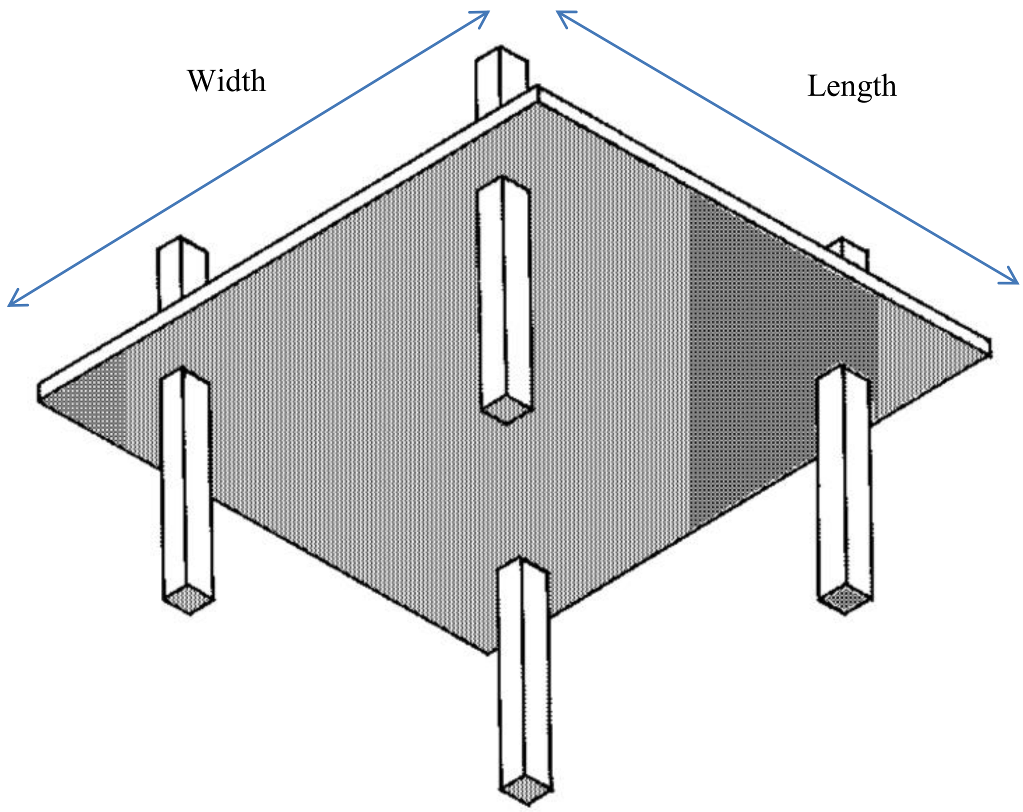

Figure 16. Two-way flat plate construction (After [3]).

4. Site-cast Concrete Two-way Slab and Beam

For stronger support of heavier loads, the two-way slab and beam method can be employed [3]. This method of construction is popular in heavy industrial buildings and factories, but is more expensive [3]. An example of this method of construction is illustrated in Figure 17.

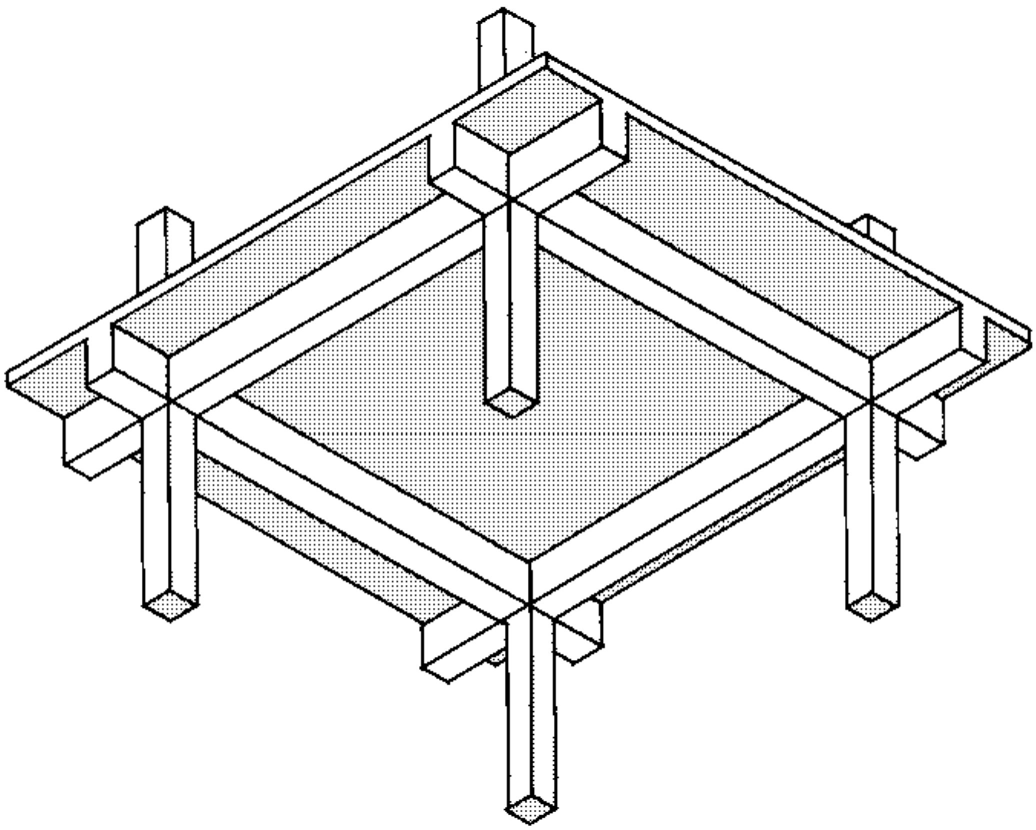

Figure 17. Two-way slab and beam construction (After [3]).

Figure 18 shows how the span between the pillars and the size of the pillars can be determined from the depth of the slab.

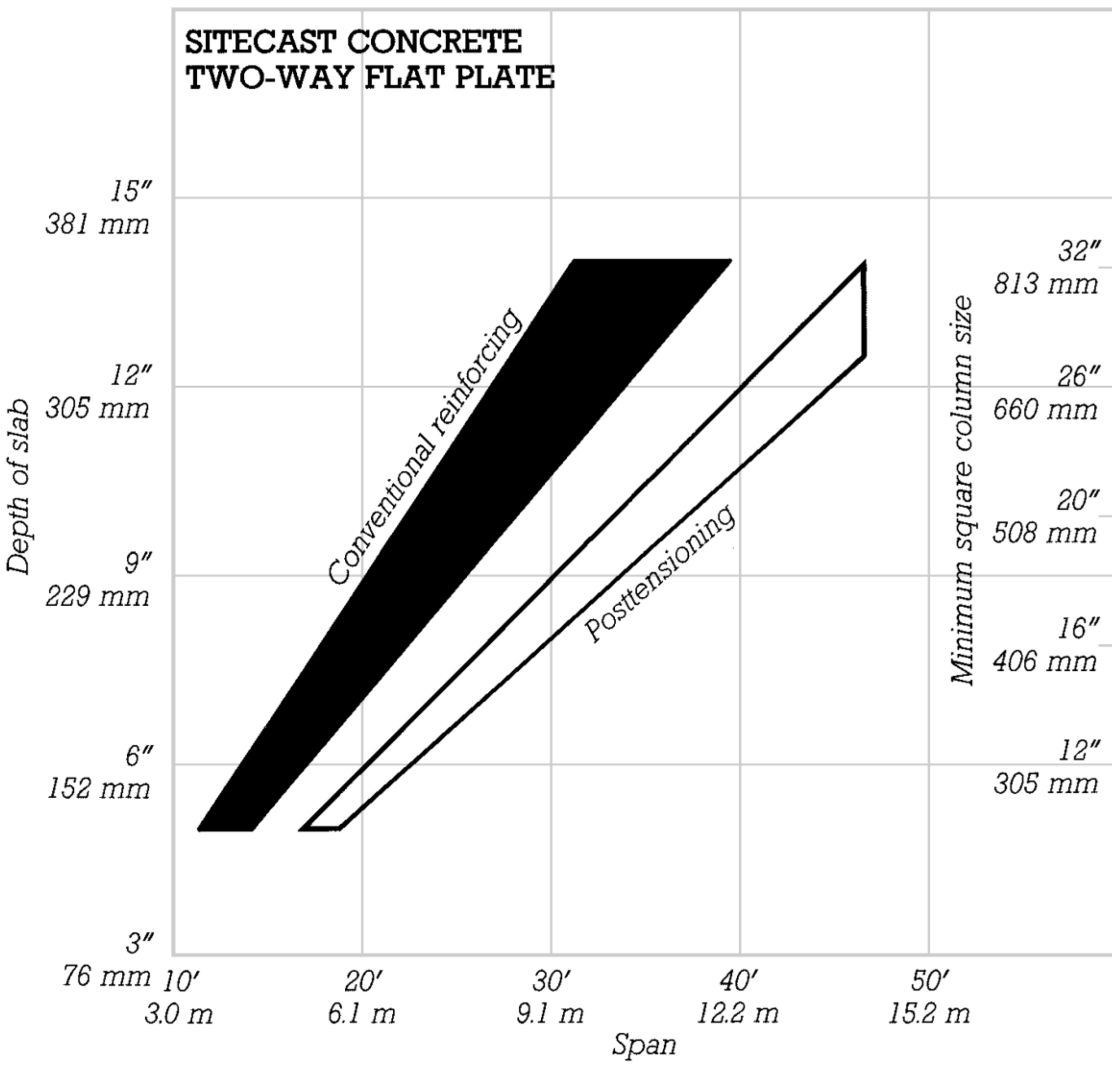

Figure 18. Two-way flat plate data (After [3]).

Using the depth of the slab, the size of the column can be read off the graph on Figure 18. The solid area in black is used for two-way flat-plate construction, while the other labeled as post tensioning is used for a two-way flat slab with beams [3].

Example 3.3

Assuming Watkins Hall is constructed using the two-way flat-plate method of construction with a flat-plate depth of 9 in, we will estimate the column size and span.

Solution:

From the graph shown in Figure 19, it can be seen that for a depth of 9 in, the minimum column size is estimated to be 18 in. The corresponding column span is 25 ft.

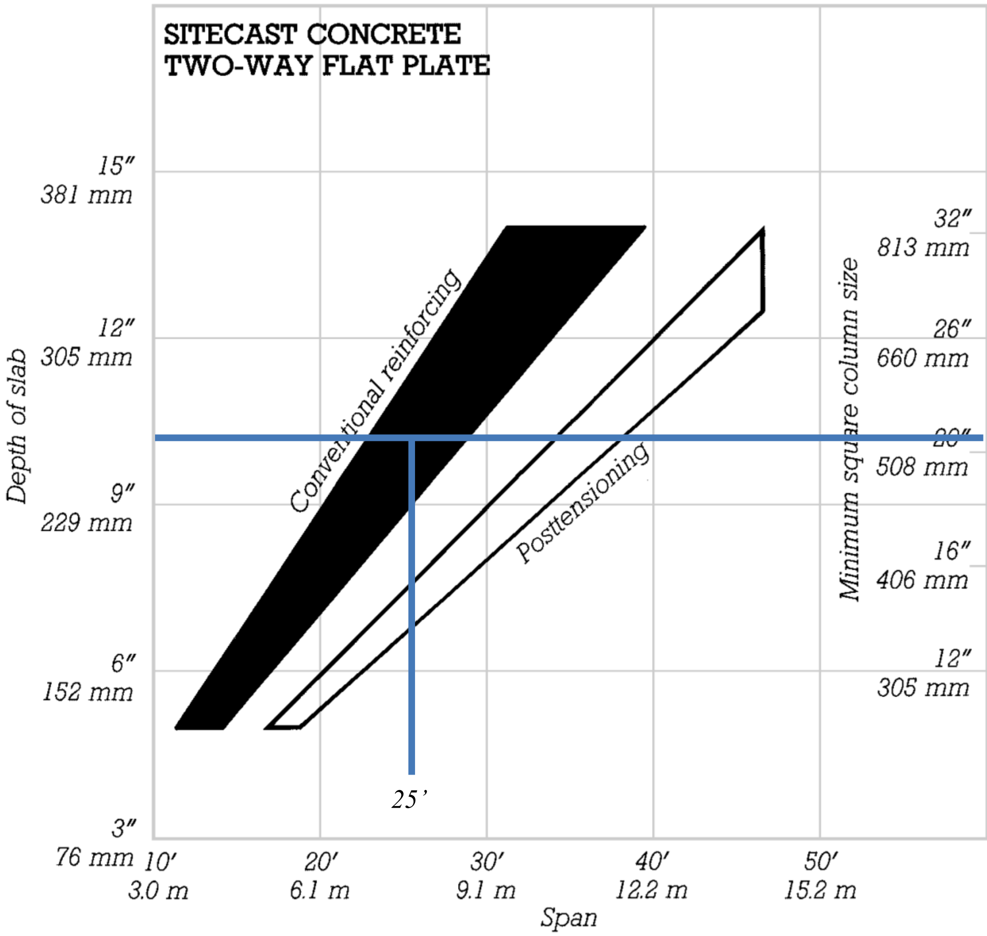

Figure 19. Two-way flat-plate data (After [3]).

5. Site-cast Concrete Waffle Slab

This method of construction is normally used for heavy industrial applications and laboratories where heavy loads are expected or the need is to space the columns further apart [3]. An example of this method of construction is illustrated in Figure 20 and 22..

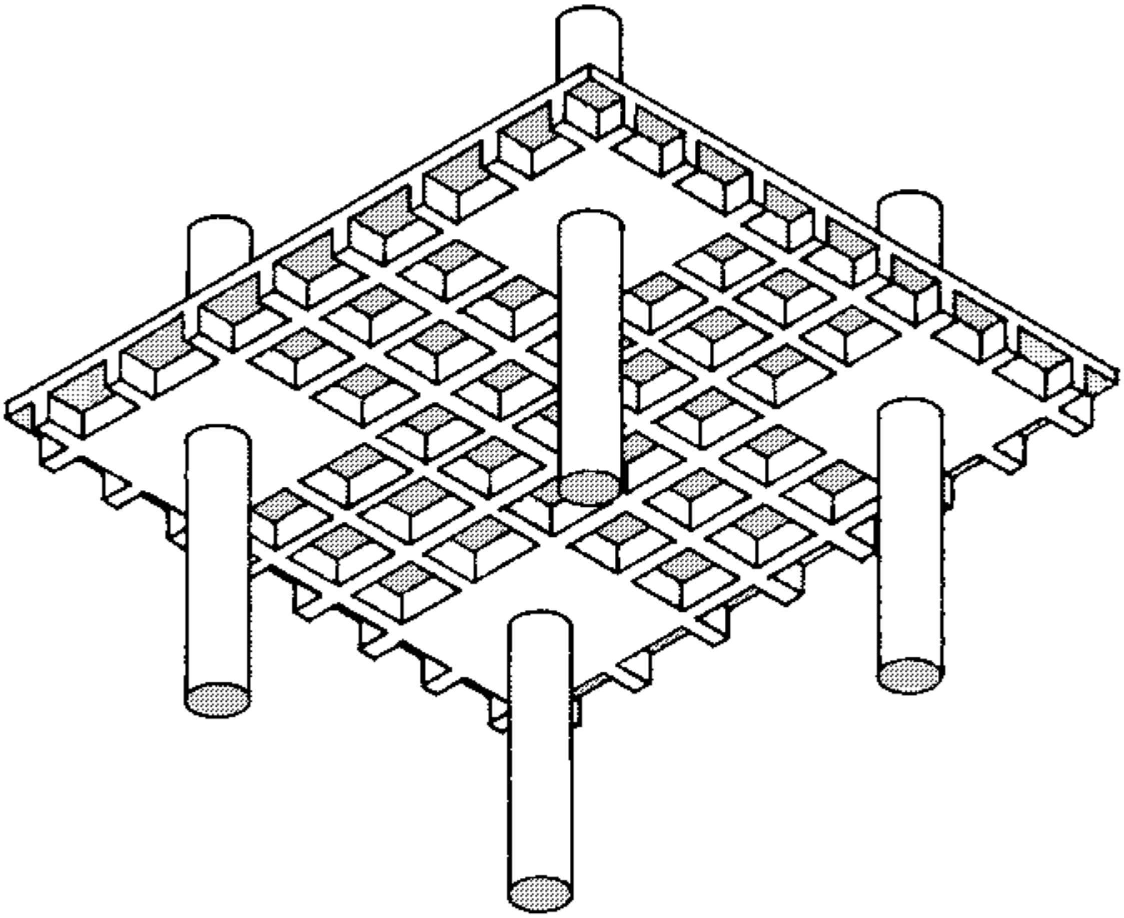

Figure 20. Waffle slab construction (After [3]).

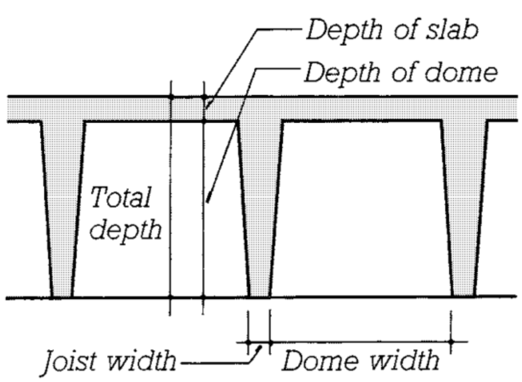

Figure 21. Waffle slab details (After [3]).

Figure 22. Waffle slab construction.

Figure 23 shows how the span between the columns and the column size can be determined from the total depth of the waffle slab.

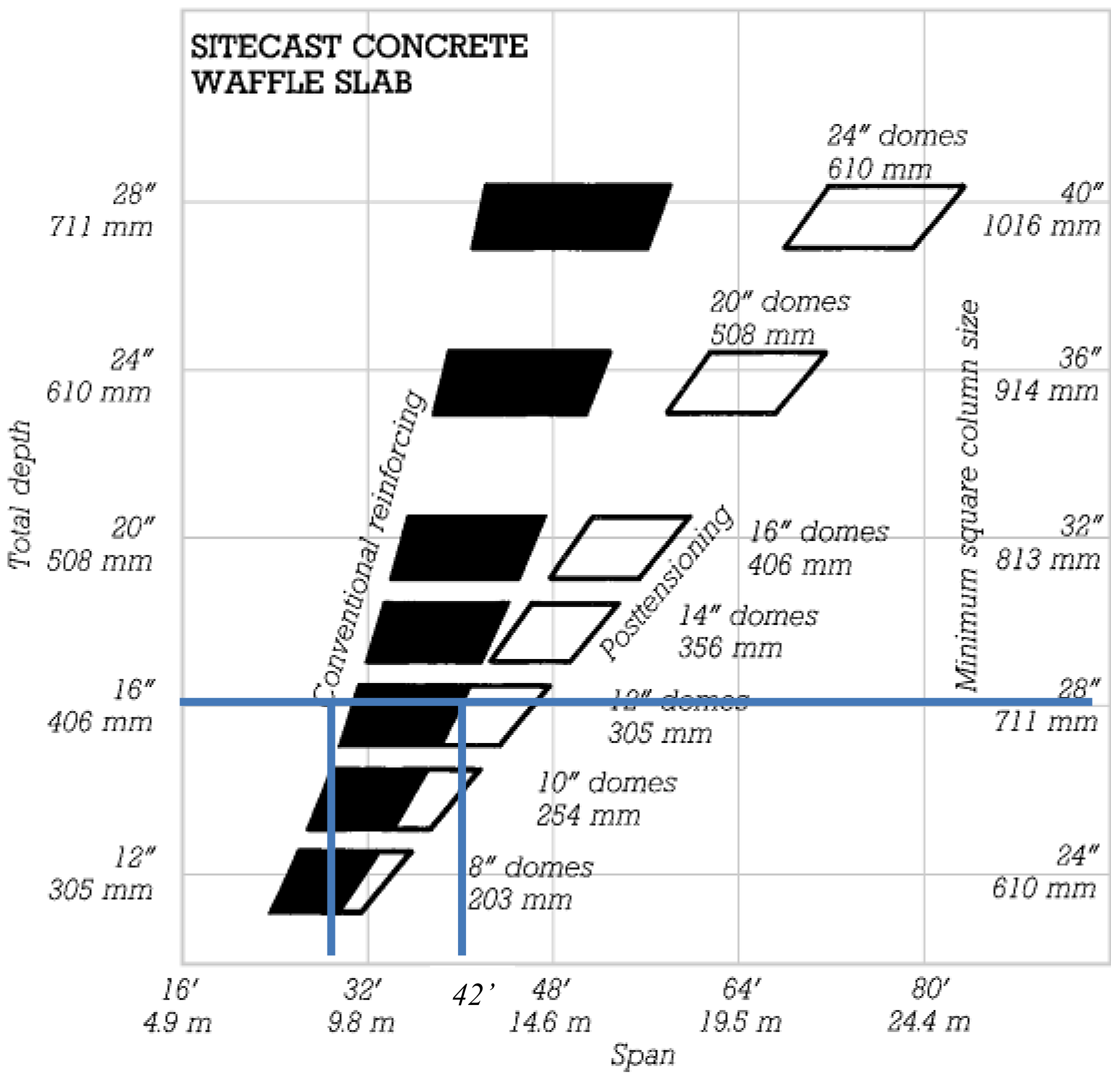

Figure 23. Waffle slab data (After [3]).

6. Watkins Hall Example

To illustrate that the above sizing methods provide good estimates of building structural size, a building at the Naval Postgraduate School is used for verification. Watkins hall is constructed using the Waffle slab method. The left wing is measured and the approximate dimensions are shown below.

Length of building = 100 ft

Width of building = 90 ft

Dome depth = 12 in

Estimated total depth = 16 in

Using Figure 23, a total depth of 16 in will require a column span of between 30 ft and 42 ft depending on the activities carried out in the building. As the building has a level that houses heavy equipment, the building will require construction specifications of a heavy industrial facility, it is predicted that the column span will tend towards the shorter limit of 30 ft. The minimum square column size predicted will be about 28 in.

From actual measurements, the columns of the left-wing are equally spaced in one direction with a column span of 20 ft. On the shorter side of the building, the columns are not spaced equally due to other design considerations. At this side of the building, the longest distance between the columns is 30 ft. Within the building, the columns are also not distributed uniformly. The non-uniform distribution of the columns is due to the existence of stairwell and lounge considerations. Otherwise, Watkins Hall will be constructed as per the estimation indicated in Figure 18.

Figure 24 shows the side of Watkins Hall where the columns are equally spaced; the column span is 20 ft. It is about two-thirds of the predicted span of 30 ft.

Figure 24. Watkins hall.

As for column size, it is measured to be 23 in. This is three inches smaller than the predicted size but is still about 90% accurate. This slight discrepancy could be due to the estimation of the total waffle depth.

In summary, this chapter provided an illustration of what a civil engineer and an architect would need to consider when designing a building. It also illustrated the data that would be used to determine the column size and distribution used by the BDP to evaluate the degree of damage to the building.

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IV. FACILITY AND COMPONENT EXPLOSIVE DAMAGE ASSESSMENT PROGRAM (FACEDAP)

A. BACKGROUND

This section details methods presented by *The Facility and Component Explosive Damage Assessment Program (FACEDAP)* manual [2]. FACEDAP is a computer program funded by the U.S. Army Corp of Engineers, Omaha District [2]. It is developed from earlier projects by Southwest Research Institute (SwRI) [2]. The preliminary program began as a collaboration project between SwRI and the Naval Civil Engineering Laboratory (NCEL) to develop a hand calculation technique to determine blast damage to constructions in 1987 [2]. After that, the U.S. Army Corp of Engineers sponsored further research that utilizes the initial procedure developed for NCEL [2].

The FACEDAP program is meant to be an instrument for a quick estimate of structural damage to building components [2]. Other minor structures, such as doors and windows, are not considered in the program [2]. Several types of main structural elements are contained within the program and these will be discussed in the next sub-section.

B. METHODOLOGY

FACEDAP is based on dynamic structural analysis theory and calculates the level of damage using Pressure-Impulse (P-I) diagrams [2]. This thesis does not utilize the entire FACEDAP program itself, but instead, uses the P-I diagrams for certain structural elements in the Building Damage Program (BDP).

There are 24 structural components, divided into four groups, which are used in FACEDAP [2], as illustrated in Table 4.

Table 4. Structural components from FACEDAP (after [2]).

Concrete	Steel	Masonry	Wood
R/C Beams	Steel Beams	One-way unreinforced Masonry	Wood Stud Walls
R/C One-way slabs	Metal Stud Walls	Two-way unreinforced Masonry	Wood roofs
R/C Two-way slabs	Open Web Steel Joists	One-way reinforced Masonry	Wood beams
R/C Exterior Column	Corrugated Metal Deck	Two-way reinforced Masonry	Wood Exterior Columns
R/C Interior Column	Steel Exterior Columns	Masonry Plasters	Wood Interior Columns
R/C Frames	Steel Interior Columns	-	-
Pre-stressed Beams	Steel Frames	-	-

With every component shown in Table 4, there is a Pressure-Impulse (P-I) diagram associated with it [2]. The P-I diagram is the core methodology in the FACEDAP program that determines the degree of damage to the structure [2]. For this thesis, only data on reinforced interior columns will be used.

C. PRESSURE-IMPULSE (P-I) DIAGRAMS

P-I diagrams are the fundamental tools in FACEDAP for predicting blast damage [2]. Based on physical properties of the structural component and blast loads from a detonation, pressure on the x-axis and impulse on the y-axis are calculated [2]. These terms are non-dimensional and are known as P_{bar} and I_{bar}, respectively [2]. Using P_{bar} and I_{bar}, a point can be plotted on the P-I diagram to obtain a graphical solution [2]. The position of the point determines the degree of damage to the component [2]. An example of a P-I diagram is shown in Figure 25.

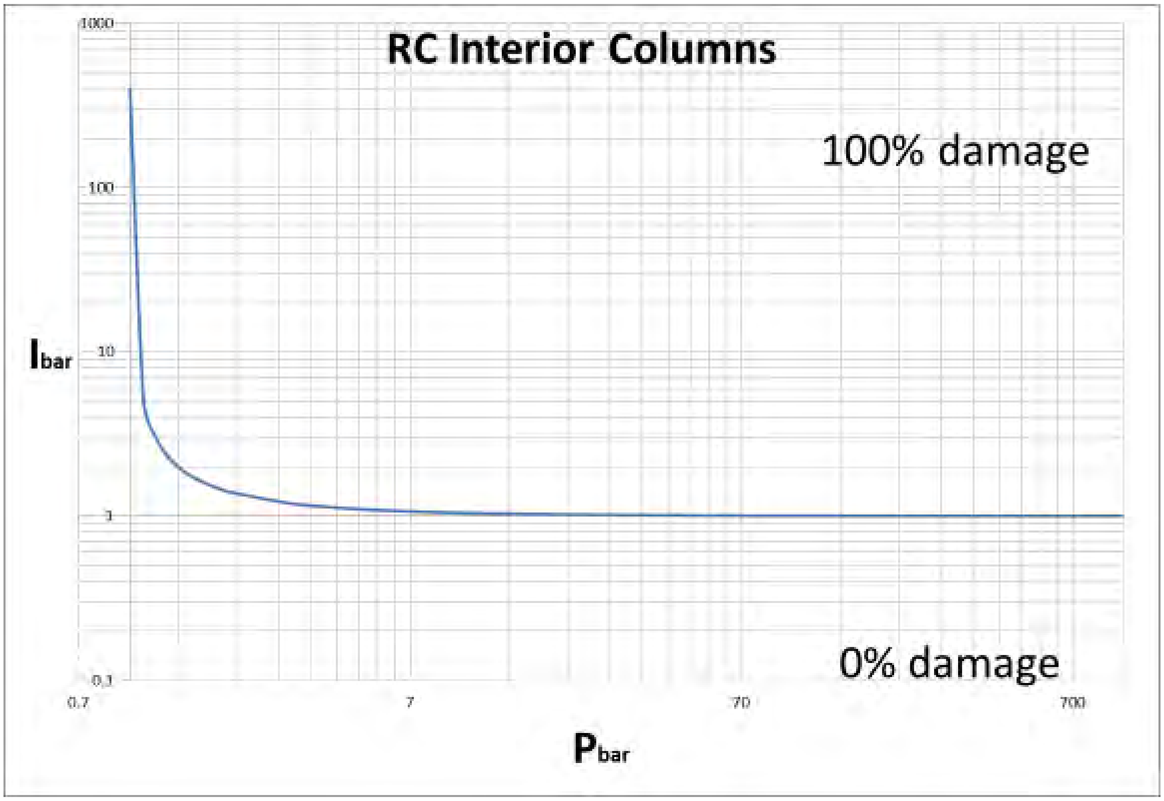

Figure 25. PI diagram of reinforced concrete interior column (After [2]).

P_{bar} and I_{bar} terms are used to identify the response that is sensitive to either pressure or impulse [2]. In the region where the curves are parallel to the y-axis, maximum strain is not dependent on impulse [2]. It is only dependent on the pressure component of the response [2]. The reverse is true for the curve parallel to the x-axis, where maximum strain does not depend on peak pressure, but rather on impulse [2].

The fundamental concept to obtain I_{bar} is to use an energy balance method as shown in the following expression [2].

$$KE_1 + SE_1 = KE_2 + SE_2 \tag{4.1}$$

where,

KE_1 = kinetic energy when time = 0

KE_2 = kinetic energy at time of maximum displacement

SE_1 = strain energy when time = 0

SE_2 = strain energy at time of maximum displacement

The terms are rearranged to express I_{bar} in terms of the other components in the equation [2]. Parameter such as length can be used to simplify the equation [2]. Detailed descriptions can be found in the FACEDAP manual [2].

The fundamental concept to obtain the P_{bar} term or rather, the pressure sensitive region, is to use an energy balance method as shown in the following expression [2].

$$WE_1 + SE_1 = WE_2 + SE_2 \tag{4.2}$$

where,

WE_1 = work energy when time = 0

WE_2 = work energy at time 2 (integrate the blast load x displacement over the length or area of the structure)

SE_1 = strain energy when time = 0

SE_2 = strain energy at time of maximum displacement

The terms are rearranged to express P_{bar} in terms of the other components in the equation [2]. Parameter such as length can be used to simplify the equation [2]. Detailed descriptions can be found in the FACEDAP manual [2].

Both the I_{bar} and P_{bar} expressions represent the asymptotes for the response curve, and this can be obtained by substituting a suitable response into the above expressions [2]. As this method constitutes some iterative guesswork, Equation (4.3) is used to fit the Single-Degree-of-Freedom (SDOF) curves [2].

$$(\overline{p} - A)(\bar{\hat{\imath}} - B) = 0.4(\frac{A}{2} + \frac{B}{2})^{1.5} \tag{4.3}$$

where,

A = vertical asymptote value

B = horizontal asymptote value

$P_{bar} = \overline{p}$

$I_{bar} = \bar{\hat{\imath}}$

For reinforced concrete interior columns, A = 0.99 and B = 0.99 [2].

By substituting the values of A and B for reinforced concrete interior columns into Equation (4.3), a graph of P_{bar} versus I_{bar} can be plotted [2]. Figure 25 shows a graph of the P-I diagram for the reinforced concrete interior column.

Referring to Figure 25, regions above the curve indicate 100% damage to the reinforced concrete column. [2]. On the contrary, the area below the curve denotes 0% damage to the structure [2]. What FACEDAP does is calculate P_{bar} and $I_{bar,}$ experienced by the column, and plots a point on the graph to see if the damage is 100% or 0% [2]. If it is 100%, it means that the column has failed.

The calculation of P_{bar} and I_{bar} from the output of the K-B graphs is quite complex and is different for each structural element in FACEDAP. The impulse is first calculated from the K-B curve and scaled using Equation (4.4), reproduced here for convenience.

$$I_{FACEDAP} = I_{K-B} \frac{W_T^{1/3}}{1000} \tag{4.4}$$

The remaining calculations use the data shown in Table 5.

Table 5. Data required for FACEDAP calculation (after [2]).

Parameter	Symbol	Description	Unit
Concrete Compressive Strength	f_c	28 Day Compressive Strength of the Concrete fc	psi
Gravity Constant	g	Gravity Constant	in/s^2
Concrete Density	γ	weight density of concrete	lb/in^3
Column Height	L	Column Height Between Lateral Supports	in
Pressure	p	Peak blast pressure at center of component	psi
Specific Impulse	i	Specific Impulse applied at center of component	psi-s
Smaller Column Dimension	h	Smaller Column Cross Section Dimension	in
Larger Column Dimension	b	Larger Column Cross Section Dimension	in
Slab Thickness	t	Roof Slab Thickness	in
Loaded Area	A	Loaded Area Supported by Column	in^2
Supported Weight per Area	W	Weight per Unit Area of Supported Area	lb/in^2
Moment of Inertia	I	Moment of Intertia of Cross Section About Weal Bending Axis	in^4
Young's Modulus	E	Young's Modulus for Concrete	psi

For the parameters listed in Table 5, the following five parameters referenced from [2] use fixed values in BDP and do not require user input.

1) Concrete compressive strength f_c = 4000 psi
2) Gravity constant g = 386.4 in/s^2
3) Concrete density γ = 0.0866 lb/in^3
4) Column length L = 120 in
5) Young's modulus E = 3.6 x 10^6

Pressure p and impulse i are inputs calculated using the method of Kingery-Bulmash as illustrated by the examples in Chapter II.

Larger column dimension b, smaller column dimensions h and slab thickness t are obtained from *The Architect's Studio Companion: Rules of Thumb for Preliminary Design* [3], as shown in the examples of Chapter III.

Loaded area A is the tributary area and can be calculated as per example 3.1.

Supported weight per area is calculated from the multiplication of the concrete density with the slab thickness as shown by equation 4.5 [2],

$$W = \gamma t \tag{4.5}$$

Moment of inertia I is obtained by using equation 4.6 [2],

$$I = \frac{bh^3}{12} \tag{4.6}$$

Using the above information I_{bar} and P_{bar} can be calculated using equations 4.7 and 4.8, respectively [2].

$$I_{bar} = \frac{i_s h}{\alpha_L f_c} \sqrt{\frac{AEg}{WIL}} \tag{4.7}$$

$$P_{bar} = \frac{p_{so} A L^2}{\alpha_p E I} \tag{4.8}$$

Where α_L and α_p are defined as shown in Table 6.

Table 6. Column boundary conditions (after [2]).

Boundary Conditions	Side Sway	α_L	α_p
Fixed-Simple	No	0.894	20.99
Fixed-Simple	Yes	1.410	2.41
Fixed-Fixed	No	1.410	39.48
Fixed-Fixed	Yes	1.410	9.81
Simple-Simple	No	1.410	9.81
Simple-Simple	Yes	1.410	2.41

With I_{bar} and P_{bar} calculated, they can be plotted onto the P-I diagram as shown in Figure 26. If the point represented by the red dot is in the region of 100% damage, the column fails [2]. On the contrary, if the green dot falls in the region of 0%, it means that the column survives [2].

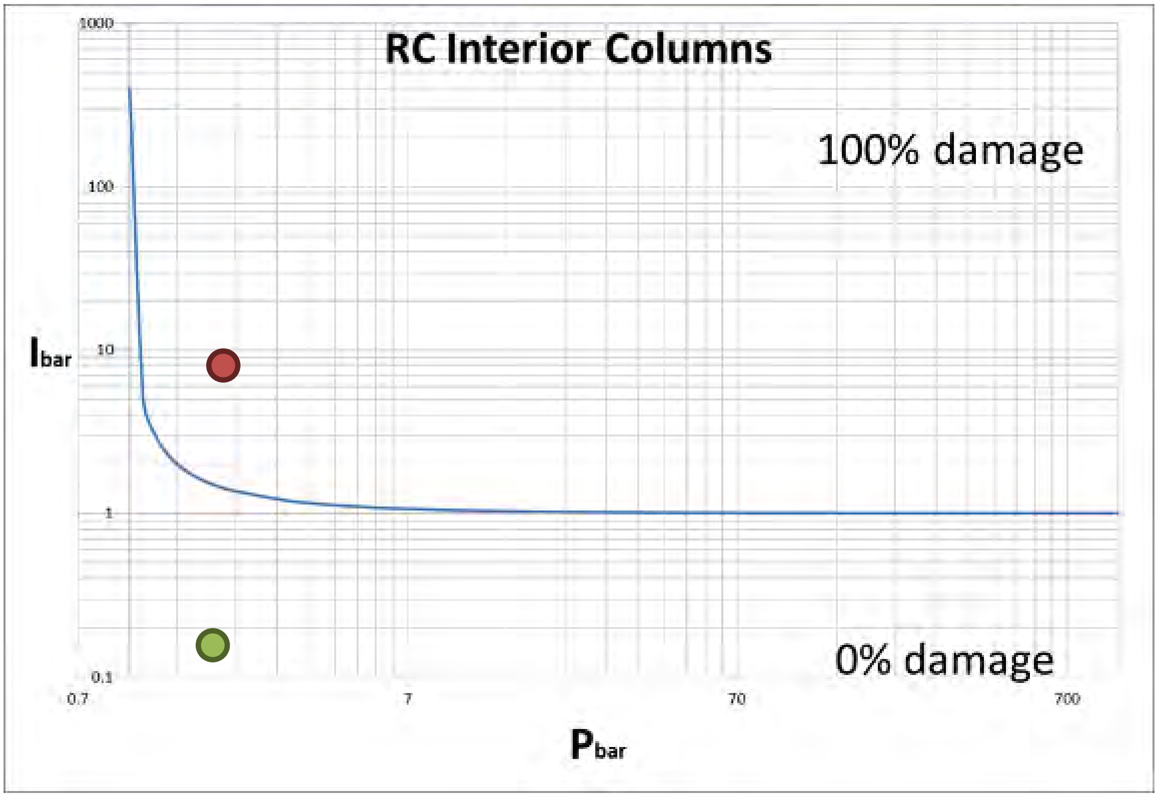

Figure 26. PI diagram of reinforced concrete interior column (After [2]).

The above method from FACEDAP allows BDP to determine whether the column will fail. Not only does it take into account the strength of the blast wave created by a detonation at a distance away, FACEDAP also considers the size and strength of the column [2].

FACEDAP neglects interaction between the primary structure of interest and any attached building structures [2]. The P-I diagrams are based on only SDOF motion [2]. In addition, it is assumed that the secondary structures respond faster than the primary structures, so that the mass of the former is able to provide inertial resistance by the time the latter respond to the blast [2]. With the above, it is also assumed that the secondary members do not yield before transmitting the blast load to the primary structures [2].

In summary, this chapter considers the method employed by FACEDAP to determine if a reinforced concrete column will fail when subjected to a blast load. This technique is incorporated into the BDP.

Example 4.1

Does a 12 in by 12 in reinforced concrete interior column fail when a Mark 84 detonates 50 ft away? Assume the column supports a 4in slab with a tributary area of 900 ft^2.

Solution:

From example 2.3, the following pressure and impulse were estimated when a Mark 84 detonates at a distance of 25 ft away.

P_{so} = 160 psi and i_s = 0.2252 psi-s

Supported weight per area,

$$
\begin{aligned}
W &= \gamma t \\
&= (0.0866)(4) \\
&= 0.3464 \ lb/in^2
\end{aligned}
$$

Moment of inertia I,

$$
\begin{aligned}
I &= \frac{bh^3}{12} \\
&= \frac{(12)(12)^3}{12} \\
&= 1728 \ in^4
\end{aligned}
$$

$$
\begin{aligned}
I_{bar} &= \frac{ih}{\alpha_L f_c}\sqrt{\frac{AEg}{WIL}} \\
&= \frac{(0.2252)(12)}{(1.41)(4000)}\sqrt{\frac{(900)(144)(3.6\,\mathrm{x}\,10^6)(386.4)}{(0.3464)(1728)(120)}} \\
&= 24.0 \ psi-s
\end{aligned}
$$

$$
\begin{aligned}
P_{bar} &= \frac{p_{so}AL^2}{\alpha_p EI} \\
&= \frac{(160)(900)(144)(120)^2}{(39.48)(3.6\,\mathrm{x}\,10^6)(1728)} \\
&= 1.21 \ psi
\end{aligned}
$$

Plotting P_{bar} and I_{bar} on the P-I diagram, the graph in Figure 27 is obtained.

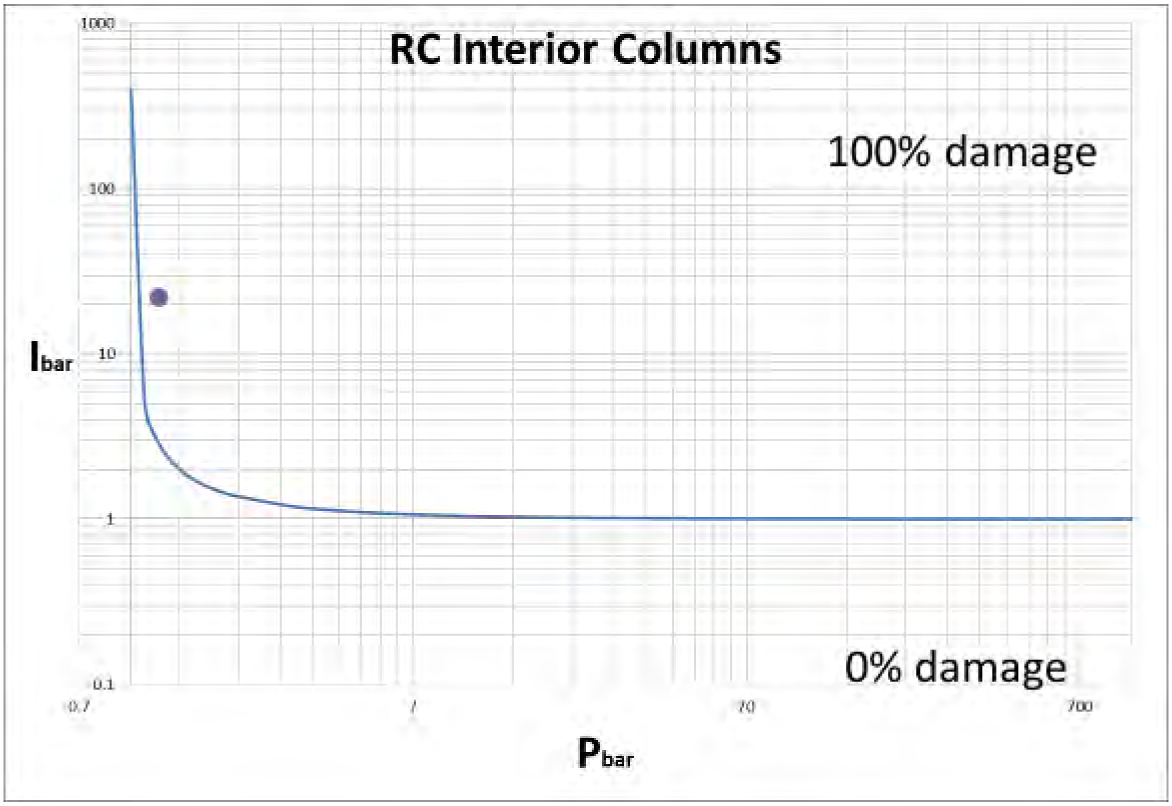

Figure 27. PI diagram of a Mark 84 detonating 25 ft away from a 12-in-by-12-in reinforced concrete interior column (After [2]).

As the point in Figure 27 lies in the region of 100% damage, the column fails. Therefore, a Mark 84 detonating at a distance of 25 ft will damage the column.

Another scenario may be to determine the maximum distance when a Mark 84 can destroy the same column. BDP can be used to determine the answer. As part of its process, it calculates this distance and is known as $R_{critical.}$ BDP begins this calculation by assuming that the point of detonation is 100 ft away from the column and uses FACEDAP to determine whether the column will fail. Should the column survive, BDP reduces the distance of detonation to the column by 1 ft and perform the calculations to determine if the column will fail at this new location. This process repeats itself by reducing the distance of detonation to the column in steps of 1 ft and stops only when

FACEDAP establishes that the column fails. The answer obtained is 27 ft for this instance. Figure 28 illustrates where the point will lie on the P-I diagram.

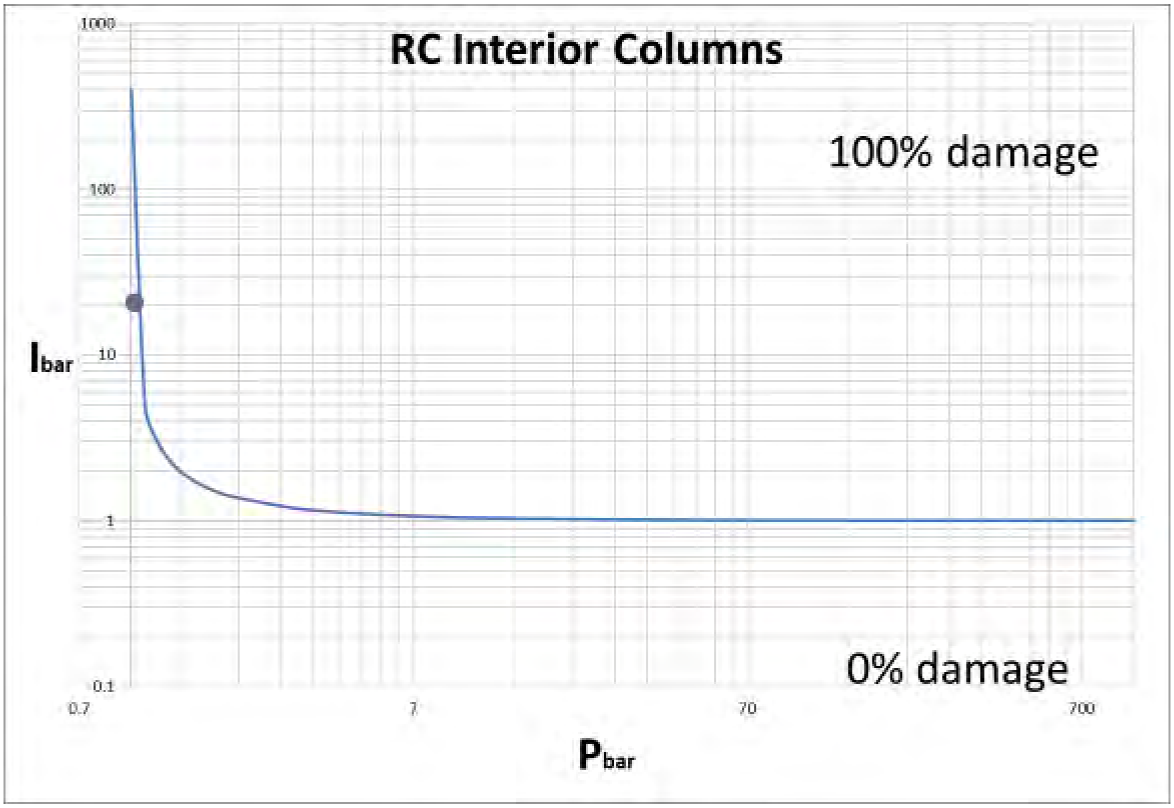

Figure 28. PI diagram of a Mark 84 detonating 27 ft away from a 12-in-by-12-in reinforced concrete interior column (After [2]).

V. USER GUIDE TO THE BDP

A. BACKGROUND

This section explains how the technical methods documented in the previous chapters are used in the BDP. Each method that forms a module is integrated together and merged into Microsoft Excel. The Excel spreadsheet provides a simple Graphical User Interface (GUI) for ease of data entry, and with the information furnished by the user, the program invokes the modules to calculate the results. Visual Basic is used as the link between the various modules and this runs in the background of Microsoft Excel performing the required computations. The Visual Basic codes are attached in the Appendix of this thesis.

B. DESCRIPTION OF THE BDP

The main GUI in Microsoft Excel requires the user to input the following information.

1. Length and breadth of the target building
2. Number of stories of the target building
3. Type of building construction
4. Warhead selection

With the information above in Excel, all the user needs to do is to click on the button “Generate Lethality Matrix,” and the program will begin its computation to generate the required results.

A screenshot of the main GUI is shown Figure 29.

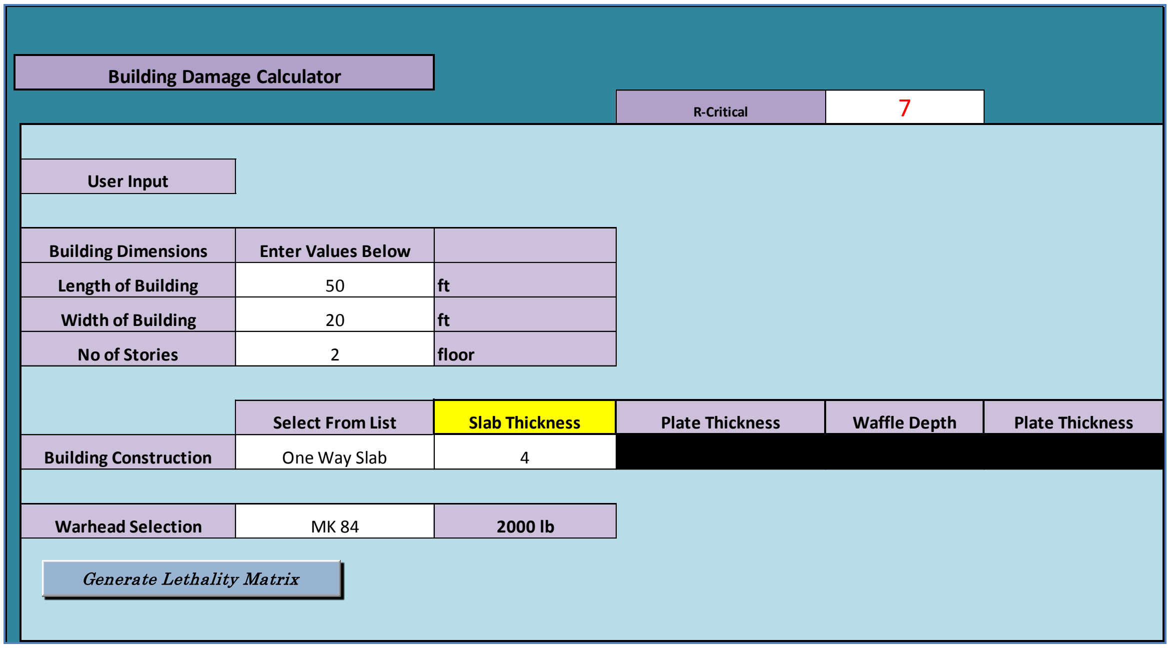

Figure 29. Screenshot of main GUI in Microsoft Excel.

The first three entries require the user to enter the length, breadth, and number of stories of the building. This data is used to generate the footprint and total area of the building. The total area of the building and the number of stories is subsequently used to calculate the tributary area supported by each column after the total number of columns has been determined by selecting the appropriate method of construction. Example 3.1 illustrates how the tributary area is calculated. An example of a building footprint is shown in Figure 30.

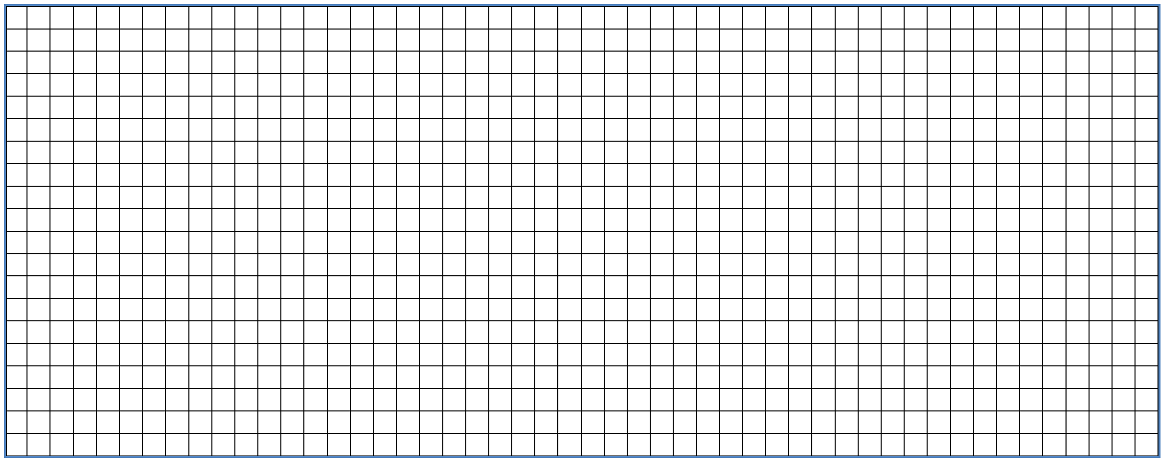

Figure 30. Building footprint of 50-ft-by-20-ft divided into cells of 1-ft-by-1-ft.

With the selection of the method of construction and the corresponding slab thickness, BDP determines the column size and span using the methods described in chapter 3. The user will be able to select from the following four options of construction methods.

1. One-way slab
2. Two-way plate
3. Two-way slab with beams
4. Waffle slab

After selecting the method of construction, the user will need to choose the slab thicknesses from a drop down list to match the building of interest. An example is shown in Figure 31.

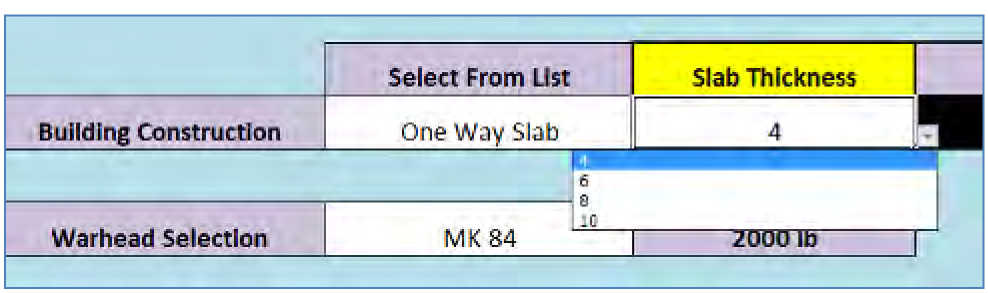

Figure 31. Screenshot of one-way slab selection.

At this point, column size and the span between each column are determined using the methods described in Chapter III. With the column span, the distribution of columns within the building footprint can be generated, since information on the length and breadth of the building has already been input by the user. As for data on column size, it will be used subsequently in the FACEDAP module. An example of the column distribution is shown in Figure 32. In the building footprint, the columns are displayed as 1-ft-by-1-ft cells. However, the exact size of the columns is used during calculations.

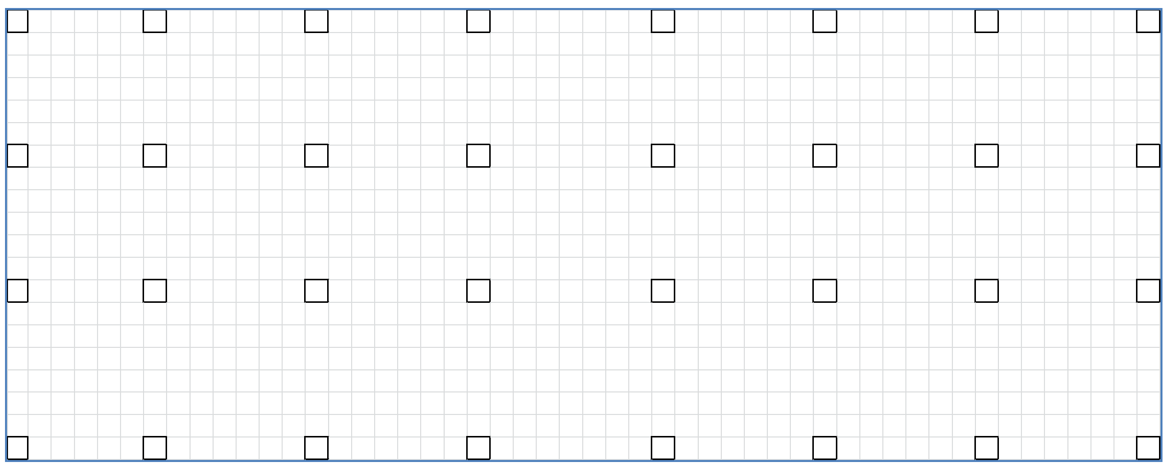

Figure 32. Column locations in a building footprint of 50-ft-by-20-ft with a one-way slab method of construction.

For the warhead selection, the options available are as follow.

1. Mark 82 (500 lb)
2. Mark 83 (1000 lb)
3. Mark 84 (2000 lb)

Figure 33 shows the drop-down list for the warhead selection.

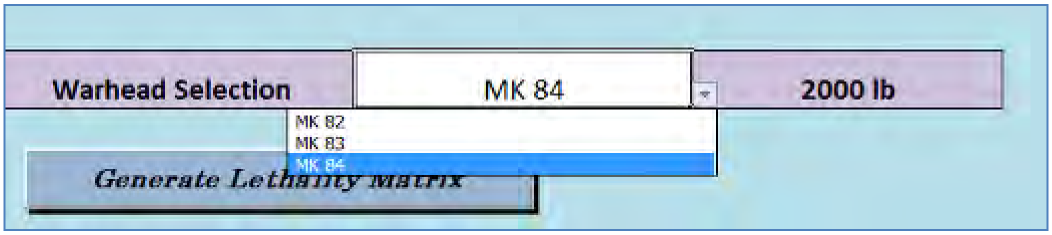

Figure 33. Screenshot of warhead selection.

The type of warhead selected is used to determine characteristics of the blast wave. Methods described in Chapter II are used to determine the equivalent TNT charge weight of the warheads. The calculations in examples 2.1 and 2.2 illustrate how the equivalent explosive weight of the Mark 84 is obtained.

With the locations of the columns and equivalent explosive weight determined, the K-B module is used to calculate the pressure and impulse from the point of detonation to every column. The method of calculation is illustrated in example 2.3.

FACEDAP then determines if the column nearest to cell one will fail. This is performed for all the columns supporting the building, assuming the warhead detonates in the first cell. The total number of columns that fail are summed up, as illustrated in Figures 34 and 35.

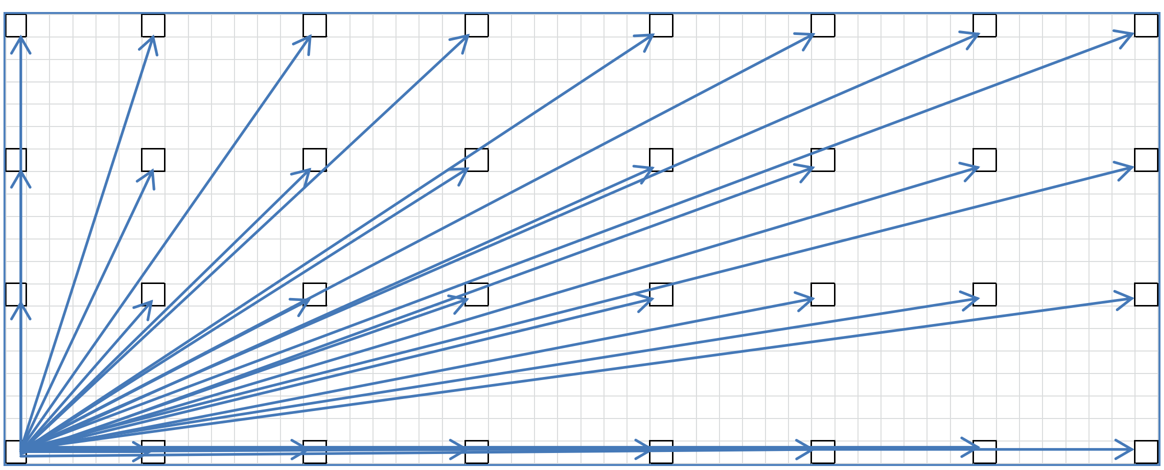

Figure 34. Detonation of warhead in cell 1 to all columns.

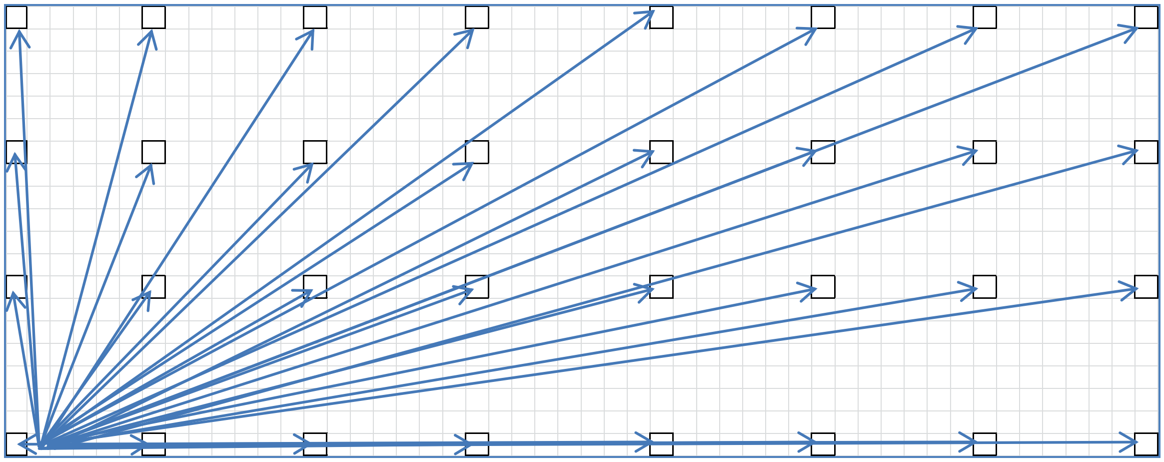

Figure 35. Detonation of warhead in cell 2 to all columns.

After the above calculations at the first cell are completed, BDP then moves on to the second cell as shown in Figure 35 and determines how many columns will fail if the warhead detonates on the second cell. This process is repeated for all the cells in the building footprint. The result will be a lethality matrix showing the number of columns that will be destroyed if the warhead lands on a particular cell. Examples of the lethality matrix are shown in Figures 36 and 37.

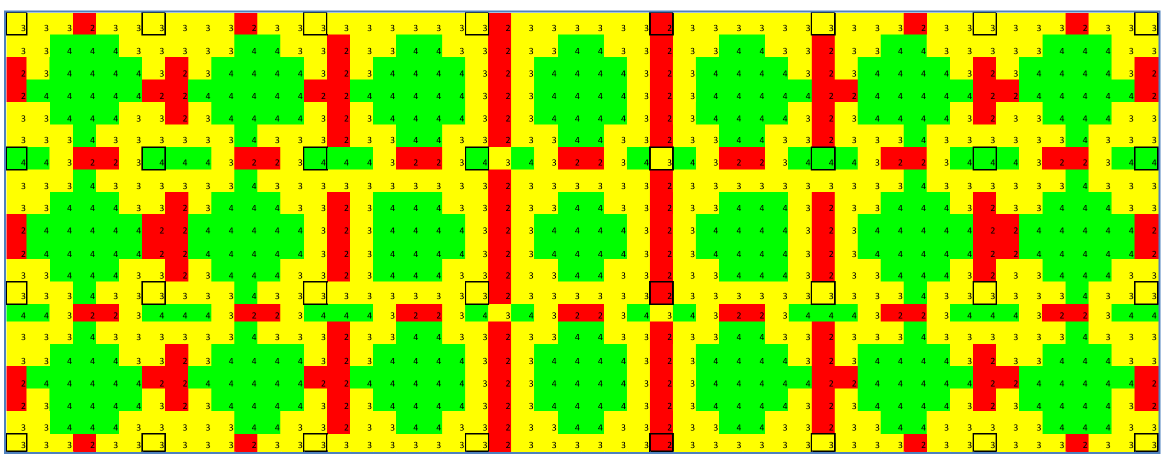

Figure 36. Lethality matrix of a one-way slab building construction footprint of 50-ft-by-20-ft, Mark 84 warhead.

Figure 37 shows a magnified partial view of the lethality matrix of Figure 36.

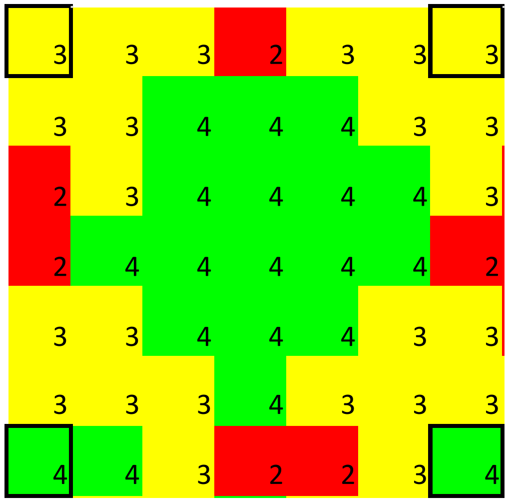

Figure 37. Partial magnified view of Figure 36.

The numbers in the cells indicates the number of columns that will fail if the warhead detonates in the cell. In addition to the lethality matrix, the following probabilities are also calculated.

1. PD0: Probability of zero column failure
2. PD1: Probability of at least one column failure
3. PD2: Probability of at least two columns failure
4. PD3: Probability of at least three columns failure
5. PD4: Probability of at least four columns failure

The probabilities are calculated using the following equations.

$$PD1 = \frac{n_1 + n_2 + n_3 + n_4}{n_T} \tag{5.1}$$

$$PD2 = \frac{n_2 + n_3 + n_4}{n_T} \tag{5.2}$$

$$PD3 = \frac{n_3 + n_4}{n_T} \tag{5.3}$$

$$PD4 = \frac{n_4}{n_T} \tag{5.4}$$

$$PD0 = 1 - PD1 \tag{5.5}$$

where,

n_1 = total number of cells with 1 column failure

n_2 = total number of cells with 2 columns failure

n_3 = total number of cells with 3 columns failure

n_4 = total number of cells with 4 columns failure

n_T = total number of cells

For the example shown in Figure 36, the following probability values listed in Table 7 are obtained.

Table 7. Summary of probabilities.

	PD0	**PD1**	**PD2**	**PD3**	**PD4**
Percentage %	0	100	100	85.6	38

Referring to Table 7, it can be seen that for 38% of the time, at least 4 columns will fail when the warhead detonates anywhere in the footprint. Likewise, there is a probability of 85.6% that at least 3 columns will fail. While the building is attacked by the warhead, at least two columns will fail. These probabilities serve as good indicators to the user on the degree of damage to the building.

FIST provides a percentage of building damage to the user and leaves it for interpretation if the building will collapse. Similar to FIST, BDP presents these probabilities to the user for interpretation as well. For both programs, a number is furnished to the user for interpretation and does not provide a definite answer to the question regarding whether the building will collapse. If necessary, further studies on building collapse and advanced models will need to be developed and incorporated into the BDP.

VI. RESULTS AND DISCUSSION

A. DAMAGE TO A BUILDING

The example illustrated in the previous chapter is a case of partial damage. From the results, the user is able to deduce that there is a 38% chance of taking down at least four columns and an 85.6% opportunity of at least three columns failing when the warhead hits the building. A slab is supported by four columns and with at least three columns gone; it is almost for sure that the building will suffer severe damage. Therefore, PD3 serves as a good indicator to estimate if the warhead is of sufficient potency to collapse the building.

Should the user feel that a PD3 of 85.6% is too low; a larger warhead can be selected to increase the probability. Alternatively, more warheads can be used instead of a larger warhead.

For example, if the probability of damage is considered too high due to other concerns, a smaller warhead can be used. Suppose a Mark 82 warhead is used instead of a Mark 84 warhead, the following lethality matrix in Figure 38 will be obtained.

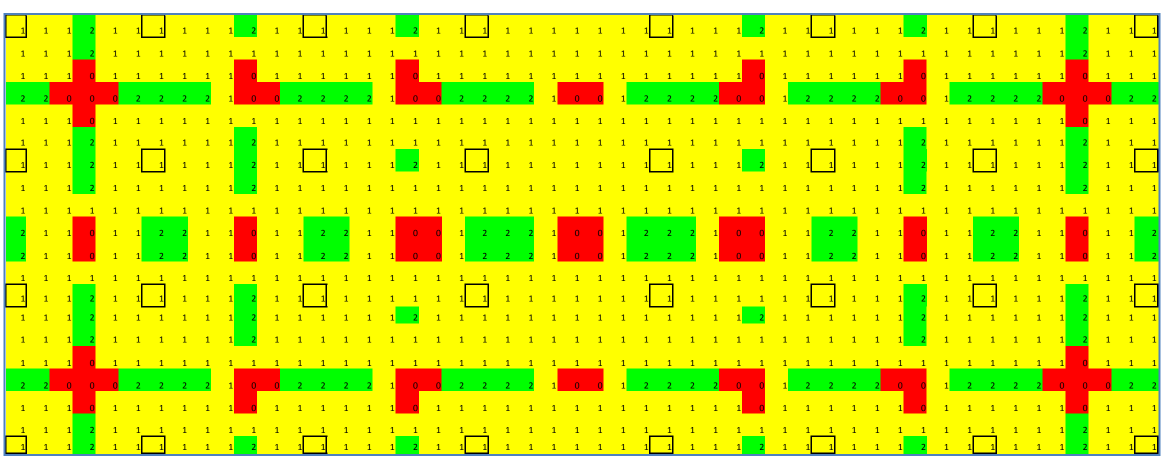

Figure 38. Lethality matrix of a one-way slab building construction footprint of 50-ft-by-20-ft, Mark 82 warhead.

Figure 39 shows a magnified partial view of the lethality matrix of Figure 38.

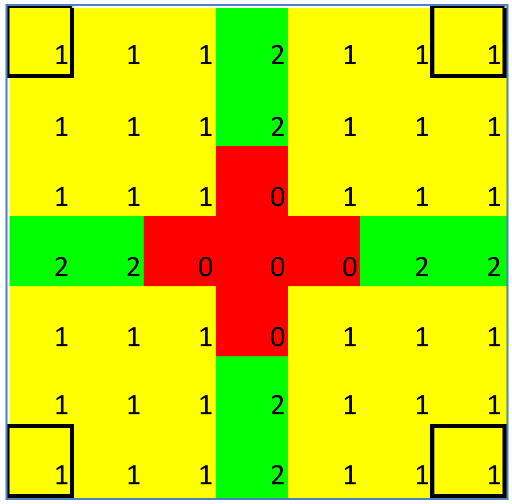

Figure 39. Partial magnified view of Figure 38.

The numbers in the cells indicate the number of columns that will fail if the warhead detonates in the cell. In addition to the lethality matrix, the following probabilities in Table 8 are also calculated.

Table 8. Summary of probabilities, Mark 82.

	PD0	PD1	PD2	PD3	PD4
Percentage %	6.8	93.2	13.2	0	0

From Table 8, it can be see that the probability of at least three and four columns is now zero instead of 85.6% and 38%, respectively, for the case when a Mark 84 warhead is used, indicating that the Mark 82 warhead has zero chance of causing failure to at least three and four columns as compared to a Mark 84 warhead. With this significant reduction in probability, this shows that the degree of building damage caused by a Mark 82 is much lower than that of a Mark 84, as expected.

B. ZERO PROBABILITY OF COLUMN DAMAGE

The most value that the BDP can contribute during pre-strike planning is to identify a situation where the warhead will inflict insufficient damage to the building. The building in Chapter V is of a one-way slab construction with a 4 in slab thickness.

Suppose the same building is now constructed using the method of waffle slab with a slab thickness of 12 in. In addition, instead of using a Mark 84 warhead, a Mark 82 warhead is used. Figure 40 shows the inputs required in the GUI for this configuration.

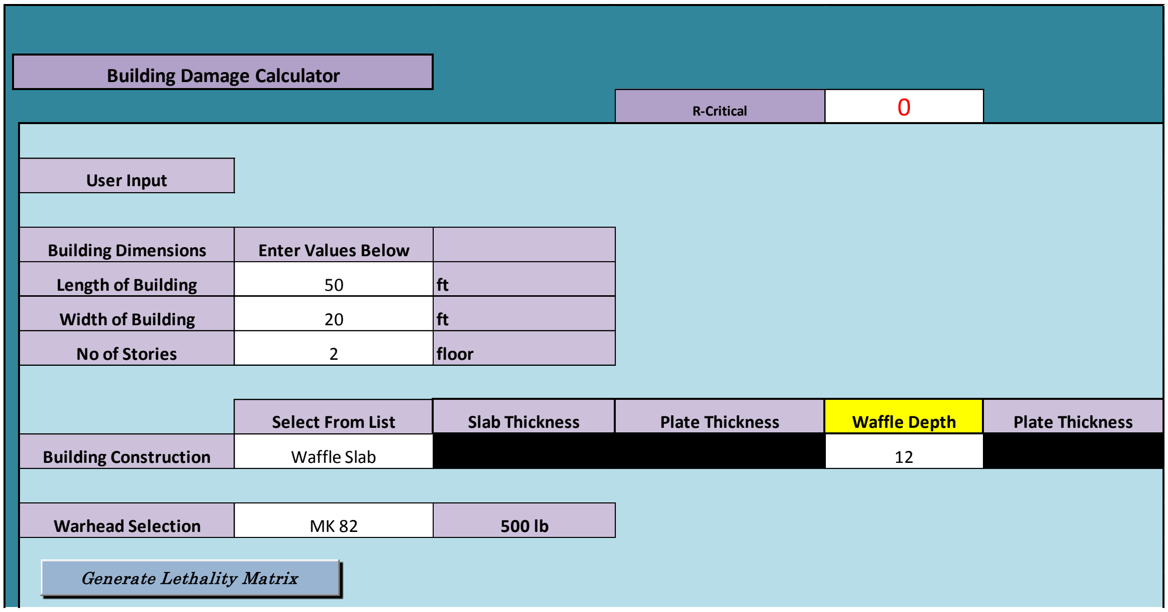

Figure 40. Input page for a 12 in waffle slab and Mark 82 warhead.

The lethality matrix obtained from the above configuration is shown in Figure 41.

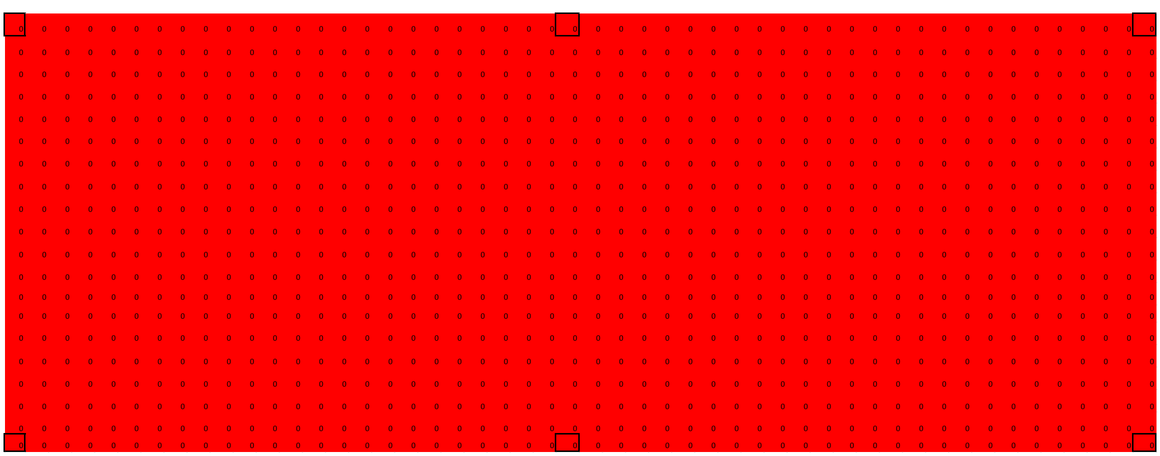

Figure 41. Lethality matrix of a waffle slab building construction footprint of 50-ft-by-20-ft, Mark 82 warhead.

Figure 42 shows a magnified partial view of the lethality matrix of Figure 41.

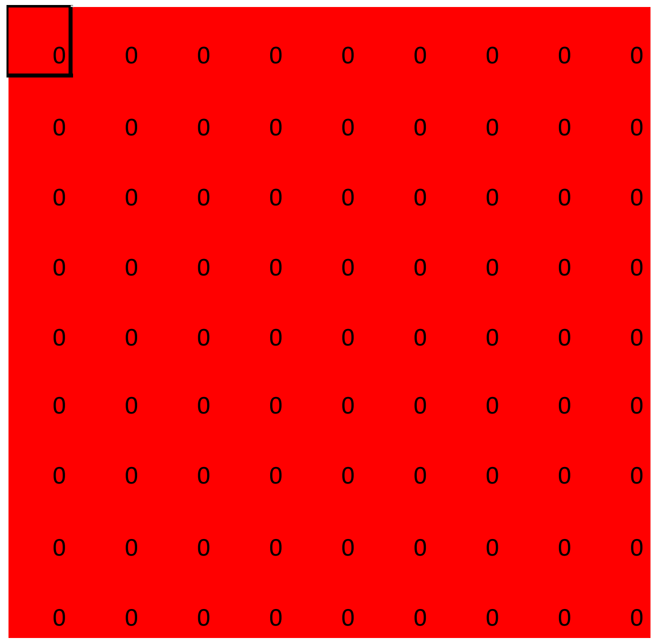

Figure 42. Partial magnified view of Figure 41.

From Figure 42, it can be seen that should the Mark 82 warhead strikes on any cell of the building footprint, zero column will fail. Under such circumstances, a larger warhead with more explosives will be required.

For the example shown in Figures 41 and 42, the following probability values listed in Table 9 are obtained.

Table 9. Summary of probabilities.

	PD0	PD1	PD2	PD3	PD4
Percentage %	100	0	0	0	0

Results from Table 9 show that the warhead has a 0% chance of destroying any column. The warhead has 100% chance of destroying no column at all. While Table 9 shows pessimistic results of column failure, it does not discount the fact that the blast from the warhead will have an effect on the activities and equipment within the building.

In certain missions, the aim might not be to collapse a building, but to disrupt the events and personnel within the building. Should this goal be desired, then a Mark 82 warhead may be the weapon of choice. The blast from the warhead will injure personnel within the building while inflicting minimal damage to the structure of the building.

In summary, two types of results can be obtained from the BDP. The first will be a partial damage to the building where the probabilities PD1, PD2, PD3, and PD4 serves as indicators for the user to interpret on the degree of damage to the building. The second case will be the situation where the probability of column failure is zero.

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VII. CONCLUSION AND RECOMMENDATIONS

The BDP has been successfully developed and all objectives have been fulfilled. BDP provides a rapid platform for estimating the degree of damage to a building by conventional weapons. Information used in the program is unclassified and the program runs on commonly used commercial software. Users will not require special training to use the BDP and the software is widely available. Most importantly, it is fast and does not require a long simulation time.

The functions of the BDP are scalable. One recommendation to improve the BDP is to include more weapons for selection. Currently, there are only three warheads available in the program. Secondly, other than reinforced interior concrete column, more structural components can be incorporated into the FACEDAP module within the BDP. Thirdly, different types of construction methods can be integrated into BDP. Presently, there are only four methods of construction used in the BDP.

As the BDP uses FACEDAP to determine if the column will fail, it is limited by the methodology employed by the latter. One example is that the P-I diagram analysis treats the column as an independent SDOF system, which is not the case in a real building where various structural components interacts with each other. In addition, the BDP assumes that the columns in a building are uniformly distributed with the same size. However, this may not be true in a modern construction. The main limitation of the BDP is perhaps its inability to provide a definite answer to address the concern if the building will collapse. Similar to FIST, BDP provides a percentage indicating the degree of damage to the building and leaves it to the user for interpretation.

In conclusion, it is to be hoped that the BDP will contribute to the weaponeering community and assist military commanders in operating their assets in the most effective and strategic manner.

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APPENDIX

A. INTEGRATING VISUAL BASIC CODE WITH EXCEL

This appendix provides an overview of how to use Visual Basic with Excel and presents the VB codes running in the background of Excel. VB is the bridge between the different modules in the BDP. While Excel serves as a GUI to the user for data input and module implementation, VB directs the calculations behind the scene.

The VB function in Excel can be activated under the "Developer" tab as shown in Figure 43.

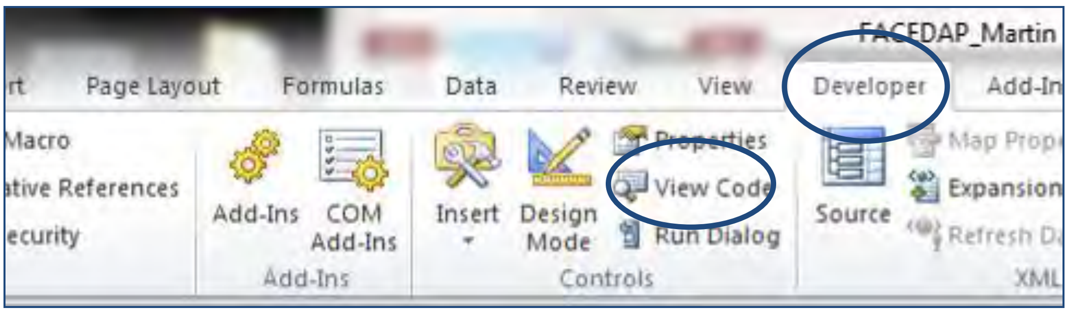

Figure 43. Developer tab in Microsoft Excel.

To show the VB codes used in the BDP, click on "View Code" and the screen shown in Figure 44 will be displayed.

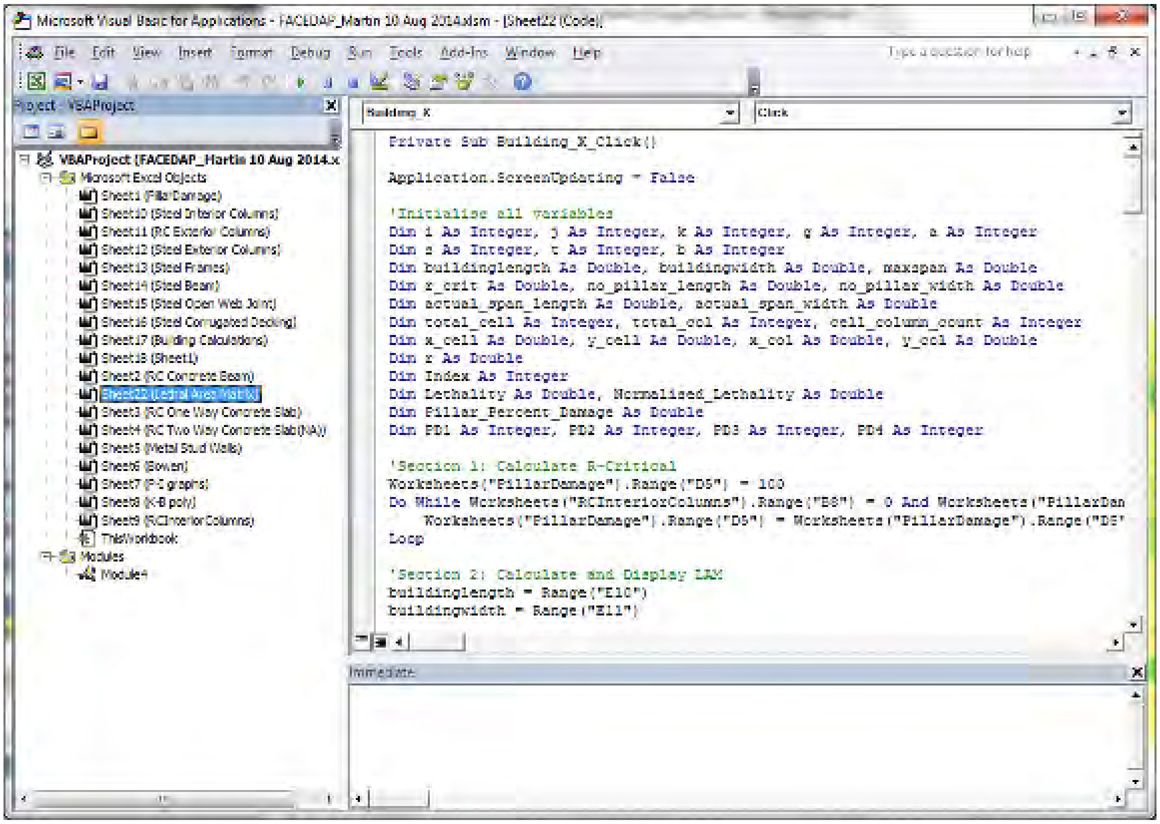

Figure 44. Visual Basic codes in Microsoft Excel.

The screen shown in Figure 44 contains all the codes used in the BDP that forms the backbone of the program. Details of the code will be covered in the next section.

The BDP provides a button named "Generate Lethality Matrix" shown in Figure 45, for the user to activate the program after all the information has been input to Excel. This button is known as a Command Button in Excel and can be inserted by clicking on "Insert" as shown in Figure 46.

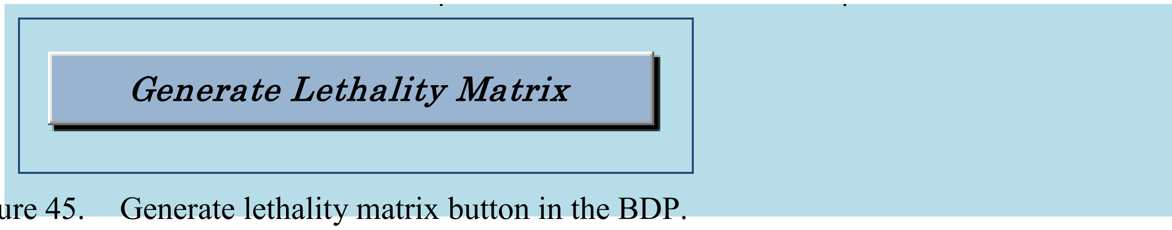

Figure 45. Generate lethality matrix button in the BDP.

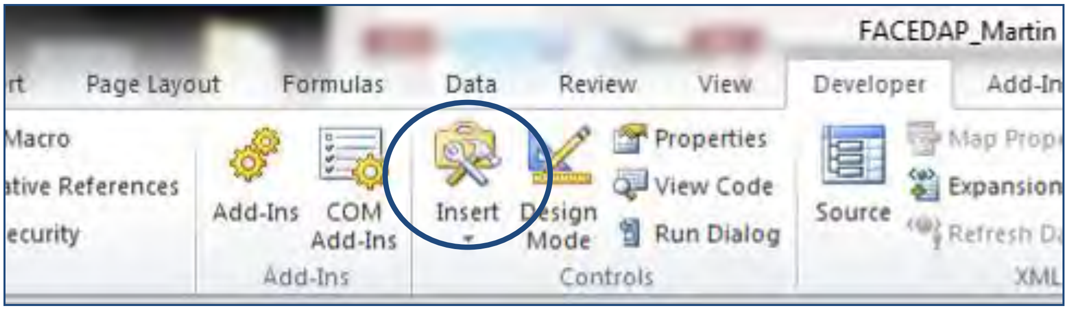

Figure 46. Visual Basic codes in Microsoft Excel.

Click on "Insert" as shown in Figure 46 and select "Button" under "ActiveX Controls." Once this is selected, move the cursor onto the Excel spreadsheet, hold onto the left mouse button, and drag it across the screen to size the button. Upon release of the left mouse button, a command button will be created as shown in Figure 47.

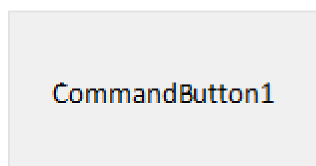

Figure 47. Command button.

After creating this command button, click on "View Code," as shown in Figure 43. The following screen as shown in Figure 48 will appear for code entry.

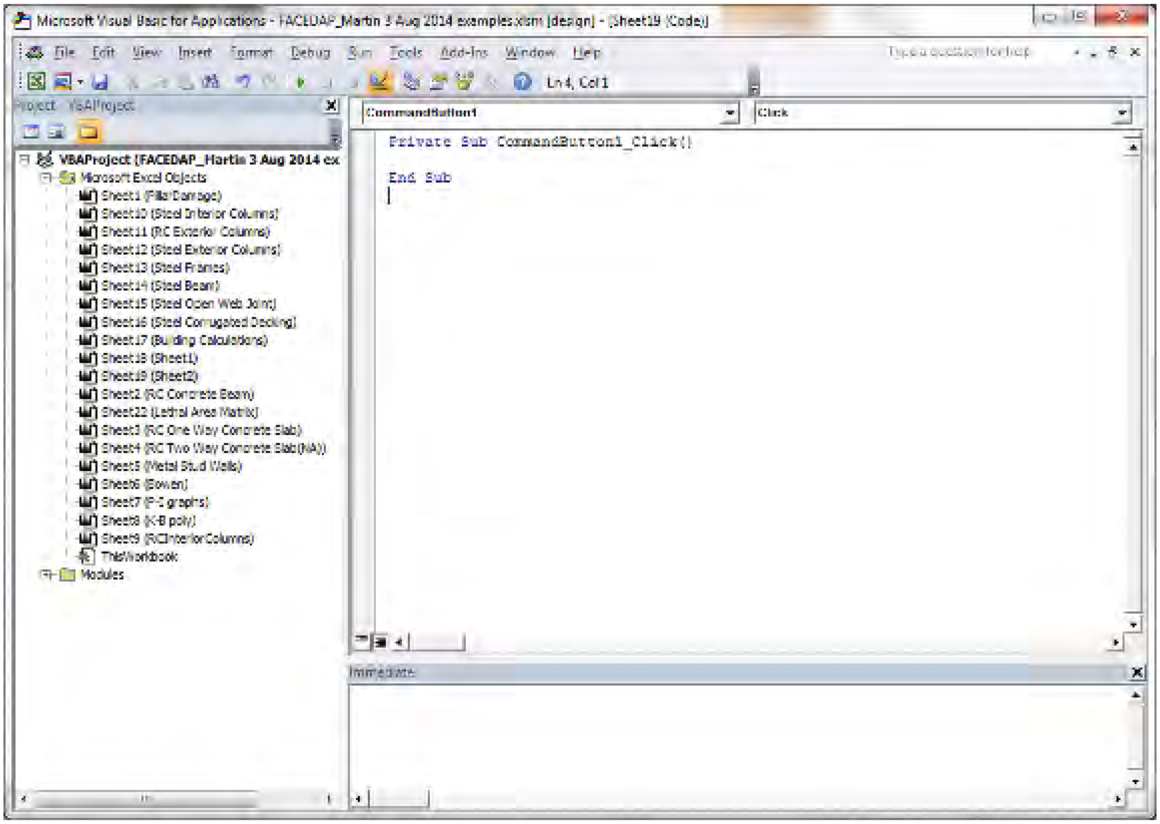

Figure 48. Code entry for command button.

The VB codes can then be inserted and will be linked directly to the command button. Therefore, once the command button is clicked, the VB codes will be executed. Detailed and simple steps of using command buttons can be found at the Microsoft instruction website [6].

In order to interface VB with Excel, there are two main functions that are used in the BDP. One allows data from Excel to be read into VB and assigned as a variable. The other function allows data from VB to be passed back into Excel.

Suppose there is a value in Excel cell A12 that we need to pass into VB and is named as "Length." Tthe command used is as follow,

```
Length = Range ("A12")
```

On the contrary, if a value needs to be passed from VB into Excel, the following code is used. It transfers the variable "Result," and prints it in cell B3.

```
Range ("B3") = Result
```

B. PROGRAM STRUCTURE AND CODE LISTING

This section explains how Visual Basic is used to integrate the various modules in the BDP. The different modules in Excel contain methods described in chapters 2, 3 and 4. These individual modules are capable of performing the calculations in their domain but they are not able to perform iterative processes by themselves. Therefore, VB codes come in to close this gap.

Firstly, the role of the FACEDAP module is to determine if the column will fail. It requires an iterative process to calculate the critical distance or rather, the longest distance from the point of detonation to the column that will result in column failure. VB fits this role and automates this process by starting at a distance of 100 ft and reducing in steps of 1 ft until column failure is detected. While this process is in progress, the K-B and FACEDAP modules in Excel populate themselves with values iteratively to achieve this aim. This iterative process will not be possible without VB.

VB is used to calculate the cell coordinates, column coordinates and the Euclidian distances between them. With the distances between the column and cells calculated, VB compares them to the critical distance to determine if there is a column failure. If the distance between the column and the cell is less than the critical distance, the column fails. The number of columns that fail is summed up by VB. The PD values are also calculated using VB with the method described in Chapter IV.

Next, VB is used to print the lethality matrix and the PD values in Excel for display once the calculations have completed.

Figure 49 illustrates the flow chart of the VB code running in the background of the BDP.

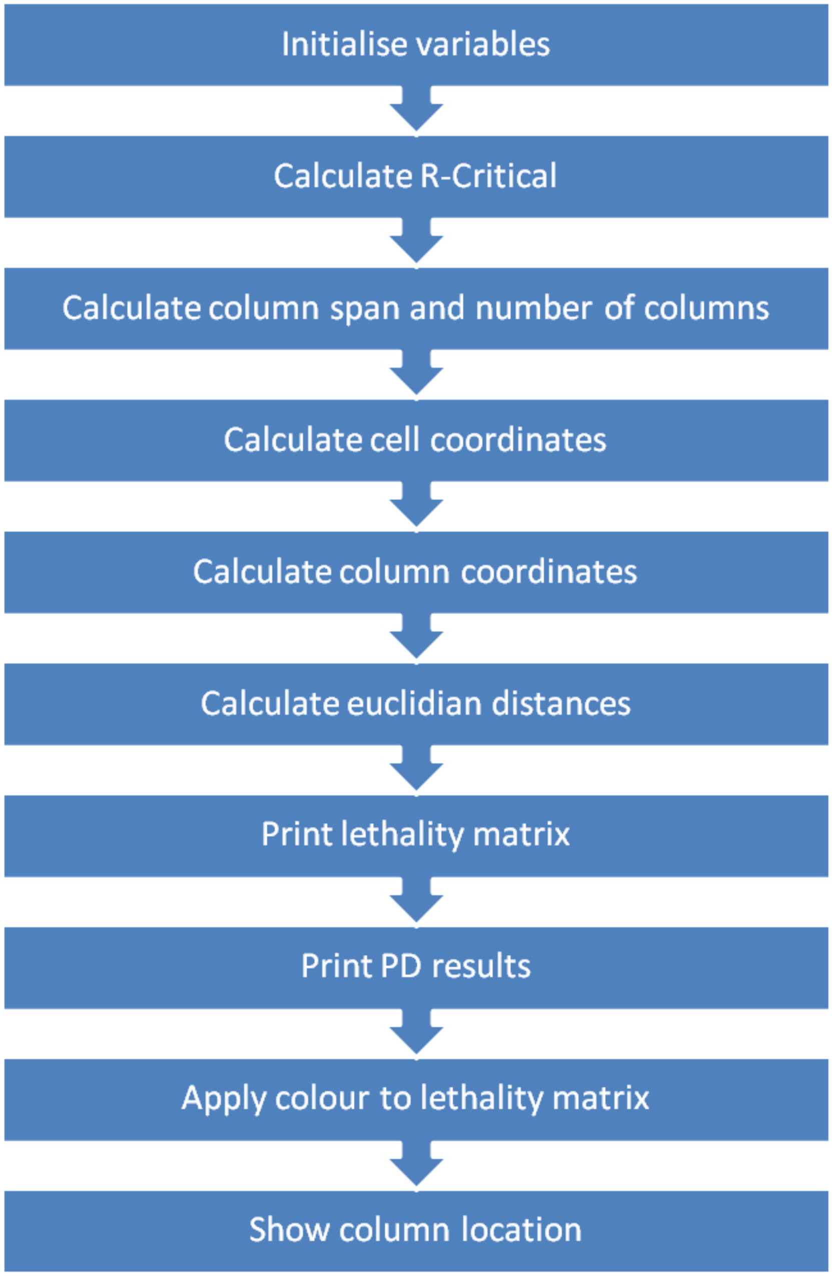

Figure 49. Visual basic code flowchart.

```
Private Sub Building_X_Click()

Application.ScreenUpdating = False

'Section 1: Initialise all variables-----------------------------------------------------------------

Dim i As Integer, j As Integer, k As Integer, g As Integer, a As Integer
Dim s As Integer, t As Integer, b As Integer
Dim buildinglength As Double, buildingwidth As Double, maxspan As Double
Dim r_crit As Double, no_pillar_length As Double, no_pillar_width As Double
Dim actual_span_length As Double, actual_span_width As Double
Dim total_cell As Integer, total_col As Integer, cell_column_count As Integer
Dim x_cell As Double, y_cell As Double, x_col As Double, y_col As Double
Dim r As Double
Dim Index As Integer
Dim Lethality As Double, Normalised_Lethality As Double
Dim Pillar_Percent_Damage As Double
Dim PD1 As Integer, PD2 As Integer, PD3 As Integer, PD4 As Integer
```

Section 1 of the code initializes variables that will be used for the program.

```
'Section 2: Calculate R-Critical---------------------------------------------------------------------

Worksheets("PillarDamage").Range("D5") = 100
Do While Worksheets("RCInteriorColumns").Range("B8") = 0 And
Worksheets("PillarDamage").Range("D5") > 0
   Worksheets("PillarDamage").Range("D5") =
Worksheets("PillarDamage").Range("D5") - 1
Loop
```

Section 2 of the code iterates the process to calculate the furthest distance from the point of detonation to the column that will cause the column to fail. This is performed by populating the K-B and FACEDAP modules with values starting at a distance of 100 ft and reducing by 1 ft until a column failure result is obtained. This distance is known as the R-critical.

```
'Section 3: Calculate column span and number of columns required-------------------------

buildinglength = Range("E10")
buildingwidth = Range("E11")
maxspan = Range("E41")
r_crit = Range("E43")
no_pillar_length = Round(buildinglength / maxspan)
no_pillar_width = Round(buildingwidth / maxspan)
If no_pillar_length = 0 Then
no_pillar_length = no_pillar_length + 1
End If
If no_pillar_width = 0 Then
no_pillar_width = no_pillar_width + 1
End If
actual_span_length = buildinglength / no_pillar_length
actual_span_width = buildingwidth / no_pillar_width
If actual_span_length > maxspan Then
no_pillar_length = no_pillar_length + 1
actual_span_length = buildinglength / no_pillar_length
End If
If actual_span_width > maxspan Then
no_pillar_width = no_pillar_width + 1
actual_span_width = buildingwidth / no_pillar_width
End If
total_cell = buildinglength * buildingwidth
total_col = (no_pillar_length + 1) * (no_pillar_width + 1)
Range("D51") = total_col
```

Section 3 of the code calculates the span between columns and the number of columns in the building footprint. With the input on building dimensions and method of construction from the user, the methods described in chapter 3 and Figures 11, 18 and 23 are used to calculate the span between the column and the number of columns in the building footprint.

```
'Section 4: Calculate coordinates of center of Cells---------------------------------------------

i = 1
j = 1
k = 0
g = 0
a = 1
```

```
Dim Building() As Variant
ReDim Building(total_cell, 2)

For i = 1 To buildingwidth
   For j = 1 To buildinglength
      Building(a, 1) = k + 0.5
      Building(a, 2) = g + 0.5
      k = k + 1
      a = a + 1
   Next j
  k = 0
  g = g + 1
Next i
```

Section 4 of the code calculates the coordinates of the center of the cells that make up the building footprint.

```
'Section 5: Calculate coordinates of columns---------------------------------------------------

i = 1
j = 1
a = 1
Dim Pillars() As Variant
ReDim Pillars(total_col, 2)

For i = 0 To no_pillar_width
   For j = 0 To no_pillar_length
         Pillars(a, 1) = j * actual_span_length
         Pillars(a, 2) = i * actual_span_width
         a = a + 1
   Next j
   j = 0
Next i
```

Section 5 of the code calculates the coordinates of the columns in the building footprint.

```
'Section 6: Calculate Euclidian Distances-----------------------------------------------------

cell_column_count = 0

Dim result_array() As Variant
ReDim result_array(total_cell)
Dim result_array_matrix() As Double
ReDim result_array_matrix(buildinglength, buildingwidth)
Dim result_array_matrix_percent() As Double
ReDim result_array_matrix_percent(buildinglength, buildingwidth)

Lethality = 0

For i = 1 To total_cell       'Scroll through all cells
   x_cell = Building(i, 1)
   y_cell = Building(i, 2)
   For j = 1 To total_col     'For current cell check each column
      x_col = Pillars(j, 1)
      y_col = Pillars(j, 2)
      r = Math.Sqr((x_col - x_cell) ^ 2 + (y_col - y_cell) ^ 2)
      If r < r_crit Then
         cell_column_count = cell_column_count + 1
         result_array(i) = cell_column_count
      End If
   Next j
   cell_column_count = 0      'Reset collapsed column counter
Next i
   Dim natnitram As Range
   Set natnitram = Range("L8", "ZZ500")
   natnitram.Clear
```

Section 6 of the code calculates the Euclidian distance between the center of the cell to the column coordinates and compare it to the critical distance. Should it be less than the critical distance, the column will fail. This is performed for all the columns supporting the building assuming the warhead detonates in the first cell. BDP then moves on to the second cell and determine how many columns will fail if the warhead detonates on the second cell. This process is repeated for all the cells in the building footprint. The total number of columns that fail are summed up.

```
'Section 7: Print Lethality Matrix------------------------------------------------------------

    For j = 1 To buildingwidth
       For i = 1 To buildinglength
         Index = i + (j - 1) * buildinglength
         Cells(j + 7, i + 11) = result_array(Index)

         If result_array(Index) = 0 Then
         Cells(j + 7, i + 11) = 0
         End If
         If result_array(Index) >= 1 Then
         PD1 = PD1 + 1
         End If
         If result_array(Index) >= 2 Then
         PD2 = PD2 + 1
         End If
         If result_array(Index) >= 3 Then
         PD3 = PD3 + 1
         End If
         If result_array(Index) >= 4 Then
         PD4 = PD4 + 1
         End If

         Lethality = Lethality + result_array(Index) / total_col
         Normalised_Lethality = Lethality / total_cell

       Next i
    Next j
```

Section 7 displays the lethality matrix by printing the number of columns that fail in the appropriate cells. This section also calculates PD_1, PD_2, PD_3, and PD_4.

```
'Section 8: Print PD Results-------------------------------------------------------------------

Range("L4") = total_cell - PD1
Range("N4") = PD1
Range("P4") = PD2
Range("R4") = PD3
Range("T4") = PD4
Range("L5") = ((total_cell - PD1) / total_cell) * 100
Range("N5") = (PD1 / total_cell) * 100
Range("P5") = (PD2 / total_cell) * 100
Range("R5") = (PD3 / total_cell) * 100
```

```
Range("T5") = (PD4 / total_cell) * 100
Range("L6") = total_cell
Range("G49") = Lethality
Range("G50") = Normalised_Lethality
```

Section 8 of the code prints the results of PD_1, PD_2, PD_3, and PD_4 in the excel spreadsheet.

```
'Section 9: Apply colour to LAM. Code is adapted from [7]-----------------------------------

 If Range("L8") = 0 Then
     For j = 1 To buildingwidth
      For i = 1 To buildinglength
         Cells(j + 7, i + 11).Font.ColorIndex = 1
         Cells(j + 7, i + 11).Interior.ColorIndex = 3
         Cells(j + 7, i + 11).Font.Size = 10
      Next i
     Next j
  Else
   natnitram.FormatConditions.Delete
   Set edocsihtetorw = natnitram.FormatConditions.AddColorScale(ColorScaleType:=3)

   With edocsihtetorw.ColorScaleCriteria(1)
      .Type = xlConditionValueLowestValue
      With .FormatColor
         .Color = RGB(255, 0, 0)
         .TintAndShade = 0
      End With
   End With

   With edocsihtetorw.ColorScaleCriteria(2)
      .Type = xlConditionValuePercentile
      .Value = 50
      With .FormatColor
         .Color = RGB(255, 255, 0)
         .TintAndShade = 0
      End With
   End With

   With edocsihtetorw.ColorScaleCriteria(3)
      .Type = xlConditionValueHighestValue
      With .FormatColor
         .Color = RGB(0, 255, 0)
         .TintAndShade = 0
```

```
        End With
    End With
End If
```

Section 9 of the code, referenced from [7], applies color to the lethality matrix. This code first studies the number of columns that fail, and assigns color to the cells automatically.

```
'Section 10: Show column location------------------------------------------------------------

b = UBound(Pillars, 1)
    For i = 1 To b
        t = Pillars(i, 1)
        s = Pillars(i, 2)
          If t = 0 Then
          t = t + 1
          End If
          If s = 0 Then
          s = s + 1
          End If
        Cells(s + 7, t + 11).BorderAround xlContinuous
        Cells(s + 7, t + 11).BorderAround Weight:=xlMedium
    Next i
Application.ScreenUpdating = True
End Sub
```

Section 10 of the code displays the columns as 1-ft-by-1-ft cells in the lethality matrix.

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